

Heavy Duty Diesel Truck and Bus Hybrid Powertrain Study

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Executive Summary

One of the U.S. military's highest priorities is increasing the fuel efficiency of its ground vehicle fleet. The U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) has commissioned this study to explore the range of commercial Medium-Duty (MD) and Heavy-Duty (HD) trucks and transit buses with diesel-electric hybrid powertrains, and to document the experiences of fleet users of these vehicles. Hybridizing trucks and buses provides the potential for much greater annual fuel savings than for passenger hybrids due to their significantly higher miles traveled and lower baseline fuel economy. Additional benefits of hybridization can include reduced maintenance, quieter operation, and improved performance.

As a result of initiatives begun by the Army through the Hybrid Truck Users Forum (HTUF), a variety of diesel-electric hybrid truck entries have come into the North American market in the last 2 – 4 years. Most U.S. truck and bus manufacturers now produce one or more hybrid models. Some of these hybrid trucks and buses are available on the 2012 General Services Administration (GSA) Vehicle Schedule. This will help non-tactical fleets on U.S. bases meet goals for efficiency improvement and partial electrification. Tactical vehicles should benefit as well through technology transfer. It should also support Department of Defense (DOD) initiatives to install micro-grids on bases that will utilize plug-in hybrid and full electric vehicles to provide two-way power flow in a Vehicle-to-Grid (V2G) system. Some MD and HD trucks and shuttle buses are now offering plug-in hybrid (PHEV) powertrain systems that have larger battery packs than do passenger PHEVs, and thus have the potential to play a role in a V2G energy storage and transfer system on a military base.

Developing hybrid-electric powertrains that will meet the unique load-carrying and duty cycle demands of large trucks and buses has required larger electrification components and energy storage mechanisms with higher operating voltages than for light duty hybrids, plus ways to handle the electrical load of on-board equipment for many truck types. The relatively low volumes per vehicle for many trucks have discouraged the introduction of hybrid powertrain technology since investment paybacks can be difficult to achieve. Government incentives have helped to stimulate demand, but the overall business case remains difficult and development of MD and HD truck hybrid powertrain technology has lagged that of passenger hybrids.

Key drivers encouraging the development of MD and HD diesel-electric hybrid truck and bus offerings include:

- Proposals to regulate the fuel consumption of medium- and heavy-duty trucks for the first time
- Government fleet efficiency mandates and electrified vehicle requirements

- Federal and state government purchase incentives
- Increasing fuel prices plus a growing price premium for diesel fuel over gasoline
- Increasing availability of hybrid-electric truck and bus offerings and supporting technologies with declining cost

Medium-duty delivery vehicles are presently one of the largest markets for hybrid trucks, while other popular applications include utility boom trucks and beverage haulers. Eaton Corp. manufactures a parallel hybrid-electric drivetrain that is used by many of the truck Original Equipment Manufacturers (OEMs). Most of the hybrid buses use series hybrid-electric drivetrains, and key manufacturers are BAE Systems, ISE Corporation, and Allison Transmission. Eaton and Daimler disclosed plans to offer significantly more powerful diesel-electric hybrid systems with larger battery packs over the next two years.

Fleet managers for commercial vehicle fleets operating diesel hybrid trucks and buses were interviewed for this study in order to gain first-hand knowledge of their experiences. Key findings include:

- Actual fuel savings have met expectations in some urban bus and delivery vehicle applications, but have fallen short in others. Route selection for hybrid delivery vehicles plays a big role in fuel savings realized, as does driver behavior.
- Maintenance savings have been significant, and hybrid propulsion battery durability has been significantly better than expected across most applications.
- Drivers generally like the hybrids, finding that they are easy to drive, offer equivalent or better performance, and may be less fatiguing.

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Acronyms

4x2	Four wheels with two driven
4WD	Four Wheel Drive
AC	Alternating Current
AFV	Alternative Fuel Vehicle
Ah	Ampere hours
APG	Auxiliary Power Generator
APU	Auxiliary Power Unit
ARB	Air Resources Board (California)
ASM	Auto-shift Manual (Transmission)
AWD	All Wheel Drive
BEV	Battery Electric Vehicle
BMS	Battery Management System
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CCE	Coca Cola Enterprises
CEU	Control Electronics Unit
CNG	Compressed Natural Gas
DC	Direct Current
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DPF	Diesel Particulate Filter
EDLC	Electric Double-Layer Capacitor
EDM	Electric Drive Motor
EPA	Environmental Protection Agency
EPTO	Electric Power Take-Off
ESS	Energy Storage System
EV	Electric Vehicle
F	Farad or Fahrenheit
FCCC	Freightliner Custom Chassis Corporation
FHA	Federal Highway Administration
FT-LB	Foot pounds (torque)
FWD	Front Wheel Drive

FY	Fiscal Year
GHG	Green-house Gas
GSA	General Services Administration
GVW	Gross Vehicle Weight
GVWR	Gross Vehicle Weight Rating
HD	Heavy-Duty (Truck)
HEV	Hybrid Electric Vehicle
HLA	Hydraulic Launch Assist
HP	Horsepower
HTUF	Hybrid Truck Users Forum
HVAC	Heating, Ventilating, and Air Conditioning
HVIP	Hybrid (Truck and Bus) Voucher Incentive Project (California)
ICE	Internal Combustion Engine
IMCOM	Installation Management Command (Army)
ISG	Integrated Starter/Generator
JCI	Johnson Controls Incorporated
KW	Kilowatt
KWh	Kilowatt hours
LB-FT	Pounds Feet (torque)
LCO	Lithium Cobalt Oxide
Li	Lithium
Li-ion	Lithium ion
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Spinel
LNG	Liquified Natural Gas
LPG	Liquid Propane Gas
LTO	Lithium Titanate
MD	Medium-Duty (Truck)
MW	Megawatt
MWh	Megawatt hours
NCA	Nickel Cobalt Aluminum
NG	Natural Gas

NHTSA	National Highway Transportation and Safety Administration
NiCd	Nickel Cadmium
NiMH	Nickel-metal hydride
NM	Newton Meters (torque)
NREL	National Renewable Energy Lab
NTV	Non-Tactical Vehicle
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
PTO	Power Take-off
RPM	Revolutions per Minute
RWD	Rear Wheel Drive
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
SDU	Safety Disconnect Unit
SOC	State of Charge
TARDEC	Tank Automotive Research, Development and Engineering Center
TC	Turbo-Charged
TTR	Through-the-Road (Hybrid)
USABC	United States Automotive Battery Consortium
V2G	Vehicle-to-Grid
V	Volt
VCU	Vehicle Control Unit
VDC	Volt Direct Current
Wh	Watt hour
Wh/kg	Watt hours per kilogram
Wh/L	Watt hours per Liter

1.0 Introduction

This study has been commissioned by the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) to explore the range of Medium-Duty (MD) and Heavy-Duty (HD) trucks and transit buses with diesel-electric hybrid powertrains, and to document the experiences of fleet users of these vehicles. It covers present and planned hybrid-electric powertrain technology and architectures and commercial hybrid truck and bus products.

- The primary powertrain focus is diesel engines and electric hybrid architectures, as TARDEC believes that diesel-electric hybrids have the greatest relevance to planned and projected military vehicle powertrain developments.
- The vehicle focus includes Class 4 through Class 6 MD trucks, vans, and shuttle buses (14,001 – 26,000 lb Gross Vehicle Weight [GVW]), and Class 7 and 8 HD trucks and transit buses (>26,000 lb GVW) that are primarily available in the North American market.
- Personal interviews were conducted with hybrid vehicle and powertrain manufacturers and the largest fleet users of hybrid-electric trucks and buses to obtain detailed insight into present and future product plans plus usage opinions and experiences not documented in other literature.

A vehicle with a hybrid powertrain utilizes two or more sources to produce, store, and deliver power to the drive wheels or power take-off (PTO). In a hybrid-electric vehicle (HEV), these two sources are normally an internal combustion engine (ICE) and an electric motor with power storage (typically a battery pack and/or ultracapacitor). Hybrid trucks and buses offer the same range of customer benefits as do light-duty hybrids, including increased fuel efficiency and decreased maintenance costs. Many of these larger vehicles can particularly benefit from hybrid technology because they consume large amounts of fuel, are in near-continuous operation, and, in many cases, do mostly “stop-and-go” driving, the scenario in which hybrids perform best.

Hybrid transit buses have been in the U.S. market for over a decade, similar to light-duty hybrids, but the technological development and market acceptance of hybrid trucks lags behind. The first passenger hybrid electric vehicle (Honda Insight) entered this market in 1999 while the first commercial diesel-electric hybrid truck was produced by Navistar in 2007.¹ The number of hybrid truck entries is still well behind the 30 passenger hybrid models now available in this market.²

¹ Navistar Press Release. (November 8, 2007). International Truck and Engine First Company to Enter Hybrid Commercial Truck Production. Retrieved from

<http://ir.navistar.com/releasedetail.cfm?releaseid=274937>

² Source: Hybridcars.com website. <http://www.hybridcars.com/hybrid-cars-list>

Trucks are classified by Gross Vehicle Weight (GVW) according to an industry standard system, with classes ranging from 1 to 8. There are now production hybrid truck or bus examples in each of these eight classes. This range of truck types and classes with examples of available hybrid-electric models in each class is shown in the table below.

Table 1: Commercial Truck Types, Classes, and Available Hybrid Examples

Truck Types	Class/GVW	Example of Available Hybrid
<u>Light Duty</u> ▪ Compact Van ▪ Delivery Van ▪ Mini-bus ▪ Pickup ▪ Step van ▪ Utility Van	Class 1 0 – 6,000 lb	 Light-duty Pickup Chevrolet Silverado 1500 Dual-Mode Hybrid
	Class 2 6,001 – 10,000 lb	 Light Delivery Van Iveco Daily Hybrid 35S12 used by FedEx UK
	Class 3 10,001 – 14,000 lb	 USPS Postal Van 2-Ton step van converted by Azure Dynamics
<u>Medium Duty</u> ▪ Boom/Bucket ▪ Cargo Van ▪ Delivery Van ▪ Light Tractor ▪ Pickup ▪ Shuttle Bus ▪ Utility ▪ Walk-in Van	Class 4 14,001 – 16,000 lb	 Shuttle Bus Ford E-450 w/Azure Balance hybrid system
	Class 5 16,001 – 19,500 lb	 Cargo Van Hino Truck 195h Diesel-electric hybrid COE

(Medium Duty cont.)	Class 6 19,501 – 26,000 lb	 Truck or Tractor Freightliner M2-106 Hybrid w/Eaton HEV system and Cummins 6.7L ISB diesel
Heavy Duty <ul style="list-style-type: none"> ▪ Cement ▪ Dump ▪ Local Delivery Tractor ▪ Moving Van ▪ Over-the-road Tractor ▪ Refuse Hauler ▪ Tanker ▪ Transit Bus ▪ Utility ▪ Yard Hostler 	Class 7 26,001 – 33,000 lb	 Moving Van Kenworth T370 hybrid w/280 hp PACCAR PX-6 diesel
	Class 8 33,001 lb and up	 Over-the-Road Tractor Peterbilt 386 Hybrid w/PACCAR PX-6 diesel

Source: Automotive Insight, company websites (based on CGGC – Hybrid Drivetrains for Medium- and Heavy-Duty Trucks)

2.0 Drivers for Medium/Heavy Duty Truck and Bus Hybridization

Synopsis

The key drivers for the recent expansion of diesel-electric hybrid medium- and heavy-duty truck and bus offerings include:

- Proposals to regulate the fuel consumption of medium-duty and heavy-duty trucks for the first time
- Government fleet efficiency mandates and Alternative Fuel Vehicle (AFV) purchase requirements
- Federal and state government purchase incentives
- Increasing fuel prices plus a growing price premium for diesel fuel over gasoline
- Increasing availability of hybrid-electric truck and bus offerings and supporting technologies with declining cost

The fuel savings potential from hybridizing trucks and buses is a key driver, since fuel cost makes up a significant portion of the annual operating cost of these vehicles. A combination (tractor-trailer) truck travels nearly six times the annual mileage of a passenger vehicle, on average, while achieving less than one-third of the fuel economy. As a result, the combination truck uses over 20 times as much fuel annually as the average passenger vehicle. A hybrid powertrain that can produce similar efficiency improvement in either vehicle type will deliver 20 times the fuel savings for the heavy duty truck than for a passenger hybrid vehicle.

In addition to the fuel savings, drivers for hybrid trucks and buses include reduced maintenance resulting in less downtime, comparable or improved performance levels (depending on powertrain calibration), and quieter operation due to engine-off at idle or not having to run the engine to power on-board equipment at a worksite.

2.1 Regulatory Drivers

Regulatory drivers that are encouraging the introduction of new hybrid trucks into the marketplace include the recently enacted U.S. government rules governing the fuel consumption of MD and HD trucks for the first time, beginning in 2014. In addition, there are multiple Congressional Acts, Administration Executive Orders, and resulting Department Performance Plans that are driving the acquisition and use of more efficient and alternative fuel trucks in Federal fleets.

2.1.1 MD/HD Truck Fuel Consumption Requirements – 2014 to 2018

The U.S. Environmental Protection Agency (EPA) and the National Highway Transportation and Safety Administration (NHTSA) finalized new rules effective November 14, 2011 governing the fuel consumption for on-road heavy-duty vehicles.³ This is the first time that MD and HD trucks have fallen under U.S. regulatory requirements for fuel consumption. These standards will be voluntary in model years 2014 and 2015, and become mandatory with model year 2016 for most regulatory categories.

Vehicles are divided into three major categories: combination tractors (semi-trucks), heavy-duty pickup trucks and vans, and vocational vehicles (like transit buses and refuse trucks). The rules include separate standards for the engines that power combination tractors and vocational vehicles. By the 2018 model year, the program is expected to achieve significant savings relative to current levels, across vehicle types.⁴

- Certain combination tractors – commonly known as big-rigs or semi-trucks – will be required to achieve up to approximately 20 percent reduction in fuel consumption and greenhouse gas emissions by model year 2018.
- For heavy-duty pickup trucks and vans, separate standards are required for gasoline-powered and diesel trucks. These vehicles will be required to achieve up to approximately 15 percent reduction in fuel consumption and greenhouse gas emissions by model year 2018.

³ Federal Register / Vol. 76, No. 179/ Rules and Regulations. (September 15, 2011). Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles. Retrieved November 5, 2011 from <http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/2011-20740.pdf>

⁴ NHTSA Press Release. (August 9, 2011). White House Announces First Ever Oil Savings Standards for Heavy Duty Trucks, Buses. Retrieved October 30, 2011 from

<http://www.nhtsa.gov/About+NHTSA/Press+Releases/2011/White+House+Announces+First+Ever+Oil+Savings+Standards+for+Heavy+Duty+Trucks,+Buses>

- Vocational vehicles – including delivery trucks, buses, and garbage trucks – will be required to reduce fuel consumption and greenhouse gas emissions by approximately 10 percent by model year 2018.

It is projected that these new efficiency standards for MD and HD trucks will result in additional hybrid powertrain trucks reaching the U.S. market. These will be accompanied by a range of other technology improvements in areas such as aerodynamics, tires, and drivelines in order to meet the new regulations.

2.1.2 Department of Defense Fleet Drivers

Multiple Congressional Acts, Administration Executive Orders, and Department of Defense (DOD) Performance Plans exist that are driving the acquisition of more efficient and alternative fuel vehicles for DOD non-tactical fleets. These include:

- Energy Policy Act 1992
 - 75% of light duty fleet acquisitions annually must be alternative fuel vehicles (AFVs)
- Energy Policy Act 2005
 - Use alternative fuel in dual-fuel vehicles
- Energy Conservation Reauthorization Act
 - Allow fleets to generate one AFV acquisition credit for every 450 gallons of pure biodiesel purchased for use in medium and heavy duty vehicles
- National Defense Authorization Act for Fiscal Year 2002 (Public Law 107-107)
 - Requires procurement of hybrid vehicles for DOD's light-duty truck requirements not covered by EP Act 2002
- Executive Order 13423
 - Reduce their petroleum consumption by 2% each year
 - Increase alternative fuel usage by 10% each year through 2015
 - Require fleets to use plug-in hybrid electric vehicles when commercially available and cost comparable
- Executive Order 13514
 - Reduce petroleum consumption by 2% annually through FY2020 (fleets of 20 vehicles)
 - Consider fleet and transportation during greenhouse gas inventory and mitigation processes
- Energy Independence and Security Act of 2007

- Prohibits federal agencies from acquiring light and medium duty vehicles that are not low greenhouse gas emitting vehicles
- Directs federal agencies to install at least one renewable fuel pump at fueling centers under their jurisdiction
- Department of Defense Strategic Sustainability Performance Plan FY2010
 - Reduce fossil fuel use
 - Reduce Greenhouse Gas (GHG) (Scope 1&2) by 34% by 2020 Relative to FY08
 - Reduce GHG (Scope 3) by 13.5% by 2020 Relative to FY08

The implementation of the new MD/HD Truck Fuel Consumption requirements for 2014 to 2018 will bring more efficient trucks to market that will help DOD fleets to meet the mandated 2% annual improvement factors in the Executive Orders noted above.

- Even if only 10 – 15% of each fleet is replaced annually, new vehicles will typically have 15 – 20% improvements in fuel efficiency vs. the five to ten-year-old vehicles being replaced.
- Replacing 10% of a fleet with vehicles rated 20% better in fuel efficiency would provide a 2% net fleet improvement.
- New electrified vehicle and alternative fuel entries will also be available in greater numbers. Since many of these have very high fuel economy ratings, addition of these vehicles to DOD fleets will further drive the fleet average to meet the 2% annual improvement requirement.

A complicating factor may be the effect of DOD budget cuts that could freeze the procurement of new, more efficient, replacement vehicles. Corresponding Non-Tactical Vehicle (NTV) fleet reduction tasks (right-sizing) are also being implemented by the Army Installation Management Command (IMCOM) for FY12 and FY13 in response to budget reductions. If older, less efficient vehicles are eliminated to meet these fleet tasks, there should be an overall improvement in fleet efficiency on a per-vehicle basis.

2.2 Business Drivers

There are multiple business drivers that have led to increasing demand for MD and HD hybrid truck and bus models in the past few years. These include Federal and State government purchase incentives, increasing fuel prices, and improved availability of the required powertrain technologies at declining cost. Hybrid powertrain technology for trucks and buses continues to be relatively expensive compared to conventional powertrains. Price premiums for diesel-electric hybrids range from \$40,000 – 70,000 per vehicle for medium duty trucks up to \$150,000 per vehicle for transit buses. Even with higher vehicle-miles traveled for trucks and recent fuel price increases, payback periods can still be quite long. Volumes on medium- and heavy-duty trucks are also much lower than for light-duty HEVs, making manufacturer investment recovery more difficult. Governments have responded with purchase incentives in the hopes of stimulating demand sufficiently to make hybrid trucks commercially viable in the market.

2.2.1 Federal and State Government Purchase Incentives

Both Federal and State incentives have been available in the U.S. in recent years to stimulate the purchase of MD and HD trucks.

U.S. - Federal

The Federal Alternative Motor Vehicle Credit, enacted by the Energy Policy Act of 2005, provided for four separate credits for different types of energy efficient vehicles.⁵ This included a category for Qualifying Heavy Hybrid vehicles, defined as “new vehicles with a gross vehicle weight in excess of 8500 pounds that meet the definition of a qualifying hybrid vehicle . . . a motor vehicle which draws propulsion energy from onboard sources of stored energy which are both an internal combustion or heat engine using consumable fuel, and a rechargeable energy storage system.” Tax credit amounts for hybrid truck models ranged from \$3,000 to \$12,000. The complete list of Qualifying Heavy Hybrid vehicles eligible for this IRS credit is shown in Appendix A: Heavy Hybrid Vehicles Qualifying for the Pre-2010 IRS Credit.

⁵ IRS Website. (Last updated 1-10-11). Qualified Alternative Fuel Motor Vehicles (QAFMV) and Heavy Hybrid Vehicles. Retrieved November 2, 2011 from <http://www.irs.gov/businesses/article/0,,id=175456,00.html>

This HEV Federal tax credit was phased out after 31 December, 2009 for Heavy Hybrid vehicles, and 31 December, 2010 for passenger cars and light trucks. The only U.S. Federal tax incentive that remains in effect for hybrid vehicles is for Plug-in Hybrids (PHEVs) ranging up to 14,000 lb GVW purchased in or after 2010. This means that Class 2b (>8,500 GVW) and Class 3 hybrid trucks can qualify for this PHEV credit. The credit amount varies based on the capacity of the battery used to power the vehicle. To be certified for this credit by its manufacturer, a PHEV must meet the following requirements:⁶

- The vehicle must be made by a manufacturer (i.e., it doesn't include conventional vehicles converted to electric drive).
- It must be treated as a motor vehicle for purposes of title II of the Clean Air Act.
- It must have a gross vehicle weight rating (GVWR) of not more than 14,000 lbs.
- It must be propelled to a significant extent by an electric motor which draws electricity from a battery which
 1. has a capacity of not less than 4 kilowatt hours and
 2. is capable of being recharged from an external source of electricity.
- Is a new vehicle acquired for use or lease by the taxpayer, and not for resale. (The credit is only available to the original purchaser of a new, qualifying vehicle. If a qualifying vehicle is leased to a consumer, the leasing company may claim the credit.)
- The vehicle is used mostly in the United States.
- The vehicle must be placed in service by the taxpayer during or after the 2010 calendar year.

A key point regarding government purchase incentives is that many truck fleets are operated by non-taxpaying entities such as federal and state agencies or utilities, and thus are not incentivized by tax credits. For these fleets, up-front buyer incentives are more effective than Federal tax credits. Ideally, such support could help shorten the payback time (in which the buyer recoups the extra cost of the hybrid through saved fuel and increased performance) to a more acceptable period, helping the industry reach the crucial tipping point where increased purchases make higher production volumes possible—which in turn brings the purchase price down.⁷

⁶ U.S. DOE Website. Federal Tax Credits for Plug-in Hybrids. Retrieved November 2, 2011 from <http://www.fueleconomy.gov/feg/taxphevb.shtml>

⁷ Center on Globalization, Governance & Competitiveness, Duke Univ. (June 10, 2009). Manufacturing Climate Solutions -- Carbon-Reducing Technologies and U.S. Jobs.

U.S. - State

Several U.S. states offer MD and HD hybrid truck purchase incentives under Clean Cities' initiatives, including California, New York, Connecticut, Texas and Colorado. The most prominent of these programs is California's Hybrid Truck and Bus Voucher Incentive Project (HVIP). The California Air Resources Board (ARB) created the HVIP to speed the market introduction of low-emitting hybrid trucks and buses.⁸ It does this by reducing the cost of these vehicles for truck and bus fleets that purchase and operate the vehicles in the State of California. The HVIP voucher is intended to reduce about half the incremental costs of purchasing hybrid heavy-duty trucks and buses. The HVIP provides vouchers of up to \$40,000 for the purchase of an eligible new truck or bus, and \$19.4 million was paid out through this program in 2010.⁹

The 2011 California HVIP voucher amounts are shown in the table below:

Table 2: 2011 HVIP Voucher Amounts

Gross Vehicle Weight in Pounds (lbs)		Base Incentive¹
5,001 – 8,500 lbs ²	Zero-Emission	\$12,000
8,501 – 10,000 lbs	Plug-in Hybrid	\$10,000
	Zero-Emission	\$15,000
10,001 – 19,500 lbs ³		\$15,000
19,501 – 33,000 lbs		\$20,000
33,001 – 38,000 lbs		\$25,000
> 38,000 lbs		\$30,000

¹ The first voucher received by a fleet is increased by \$5,000. Vouchers for ARB-certified hybrid vehicles above 14,000 lbs are increased by \$5,000.

²The first voucher received by a fleet is increased by \$3,000, for a total of \$15,000.

³ Zero-emission commercial vehicles in this weight category are eligible for \$20,000. Public school districts receive an additional \$10,000 for school buses. See Eligible Vehicle list for specific voucher amounts.

Source: California ARB HVIP Website. Retrieved from <http://www.californiahvip.org/>

⁸ ARB HVIP Website. Retrieved November 1, 2011 from <http://www.californiahvip.org/>

⁹ Hall, Jamie, CALSTART. (October 11, 2011). Remarks at 2011 HTUF National Conference.

As of December, 2011, there are 131 unique MD and HD hybrid truck and bus models listed on the HVIP website that are eligible for these purchase incentives in California.¹⁰ Note that some of these are a single truck model that spans multiple GVW categories, thus qualifying for different incentive amounts.

At the October, 2011 Hybrid Truck Users Forum (HTUF) annual conference, several new state and city incentive programs were announced for hybrid trucks and buses:

- Maryland Governor Martin O’Malley unveiled two initiatives for Maryland truck owners to incentivize the purchase of all-electric heavy-and medium-duty trucks and idle reduction technologies for Class 6 to 8 heavy trucks.
- New York City announced it was close to unveiling its clean truck purchase voucher.
- California indicated it is expanding its HVIP voucher to include lighter commercial e-trucks and work site idle reduction systems. Two additional changes coming to the program include a new lower weight class that makes the Ford Transit Connect Electric eligible for funding, and, in November, school buses will get an additional \$10,000 over current funding levels.¹¹

Canada

Some provinces in Canada are offering significant incentives for the purchase of PHEV and BEV vehicles that can include trucks. This will provide additional stimulus for the development and sale of these vehicles in the North American market. Incentives are presently available in Ontario, Quebec, and British Columbia.

- **Ontario** - The EV incentive program applies to new, highway capable, plug-in hybrid electric vehicles (PHEVs) or battery electric vehicles (BEVs) purchased on or after July 1, 2010. The value of the incentive is based on the vehicle’s battery capacity and ranges from \$5,000 for a 4 kWh battery to \$8,500 for a 17kWh battery. The EV incentive program is open to persons, businesses, municipalities, non-government organizations and non-profit groups. Applicants can receive incentives for no more than five vehicles per calendar year. The value of the incentive for leased vehicles is scaled to the term of the lease.¹²

¹⁰ HVIP Eligible Vehicles. Retrieved November 4, 2011 from <http://www.californiahvip.org/eligibleveh.asp>

¹¹ CALSTART website, 2011 HTUF Recap. Retrieved December 4, 2011 from <http://www.calstart.org/projects/hybrid-truck-users-forum.aspx>

¹² Ontario Ministry of Transportation website. Retrieved November 5, 2011 from <http://www.mto.gov.on.ca/english/dandv/vehicle/electric/electric-vehicles.shtml>

- **Quebec** – Has a 2011 – 2020 Electric Vehicle Action Plan in place that includes a variety of initiatives that cover electrified trucks and transit buses.¹³
 - Announced a five-year program in June 2009 that includes a subsidy for the purchase of hybrid or electric trucks equivalent to 30% of the price differential versus a gas-powered vehicle, up to a total of \$15,000 per vehicle. Businesses and municipalities are eligible.
 - Has provided refundable tax credits since January 1, 2009 of \$3,000 for plug-in hybrid vehicles and \$8,000 for all-electric vehicles. As of January 2012, these tax credits are being replaced by rebates ranging from \$5,000 – 8,000 depending on the battery's charge capacity. The rebate applies to new PHEV and BEV vehicles equipped with a minimum 4 kWh battery. Hybrid vehicles must have energy consumption not exceeding 5.27 liters/100km if gas-powered and 4.54 liters/100km if diesel-powered.
 - In March 2010, announced a new 60% amortization rate for new hybrid and electric trucks weighing over 11,778 kg used primarily for freight transportation. The rate was previously 40%. This measure provides financial support to help the trucking industry cover the high purchase price of the new generation of motors, and secure the industry's cooperation in efforts to reduce GHG emissions.
 - Transit authorities are eligible for the Government Mass Transit Assistance Program, covering up to 75% of the extra cost of purchasing electric powered or hybrid buses, and the Government Assistance Program for Improving Energy Efficiency in Private Ground Transportation, which cover up to 50% of the purchase price of electric or hybrid buses, up to a maximum of \$500,000.
- **British Columbia** - Effective December 1st, 2011, incentives of up to \$5,000 per eligible clean energy vehicle will be available to B.C. residents, businesses, non-profit organizations, and local government organizations. Incentives will be available until March 31st, 2013 or until available funding is depleted (whichever comes first).¹⁴ Incentives for Plug-In Hybrid Electric Vehicles / Extended Range Electric Vehicles are:
 - Battery capacity of 4.0 - 9.9 kWh – \$2,500
 - Battery capacity of 10.0 - 14.9 kWh – \$3,500
 - Battery capacity of 15.0 kWh and greater – \$5,000

¹³ Electric Vehicles: 2011 – 2020 Quebec Action Plan. Retrieved November 5, 2011 from <http://www.vehiculeselectriques.gouv.qc.ca/english/pdf/action-plan.pdf>

¹⁴ British Columbia Clean Energy Vehicle Program. Retrieved November 5, 2011 from <http://www.livesmartbc.ca/incentives/transportation/index.html#cevinbc>

2.2.2 Fuel Prices and Consumption

Fuel prices in the U.S. have been steadily increasing over the last three years following the sharp decline from the oil price spike in mid-2008. In addition, the price premium for diesel fuel over gasoline has widened recently. The average U.S. diesel fuel price was \$0.10 per gallon more than gasoline in May, 2011, but this difference grew to \$0.50 per gallon by year-end, as shown in the figure below.

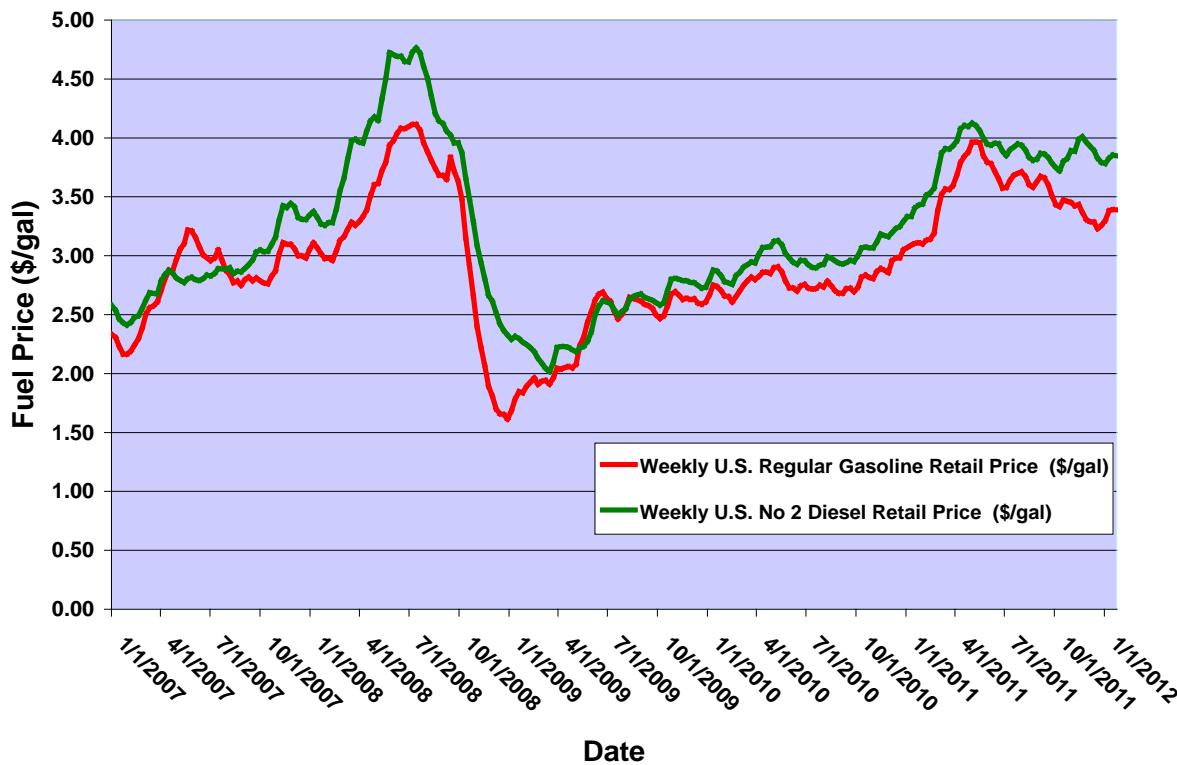


Figure 1: U.S. Retail Regular Gasoline and Diesel Fuel Prices - 2007 through 2011

Source: Automotive Insight. Data from U.S. Energy Information Administration (EIA)

Medium- and heavy-duty trucks and buses comprise just 4.6% of the U.S. on-highway vehicle fleet, but consume 27.6% of the total fuel. This is due to both the lower relative fuel efficiency of these vehicles and the higher annual vehicle miles traveled. Fuel cost is a key component of the overall operating cost for trucks and buses, and increases in fuel price have a much greater impact than for light-duty vehicles. A price premium for diesel fuel compounds this impact, since most medium- and heavy-duty trucks and buses are diesel-powered. The net effect is that the opportunity cost is higher for

technologies such as hybridization that can reduce the fuel consumption of trucks and buses.

The table below shows annual fleet mileage and fuel usage statistics as compiled by the U.S. Federal Highway Administration (FHA) for 2009 (most recent year available).¹⁵

Table 3: U.S. Highway Statistics – 2009

ANNUAL VEHICLE DISTANCE TRAVELED AND FUEL CONSUMPTION – 2009 BY VEHICLE TYPE						
Item	All Light-Duty Vehicles <u>1/</u>	Single-Unit Trucks <u>2/</u>	Combination Trucks <u>3/</u>	Sub-total All Trucks	Buses	Total All Motor Vehicles <u>4/</u>
Vehicles Regis. (000)	234,468	8,356	2,617	10,973	842	246,283
Avg Miles Trav/Vehicle	11,218	14,380	64,132	26,246	17,052	11,618
Avg Fuel Consump/Veh (gal)	517	1,956	10,748	4,053	2,219	661
Avg Miles per Gal Fuel	21.7	7.4	6.0	6.5	7.2	17.6

1/ Light Duty Vehicles - passenger cars, light trucks, vans and sport utility vehicles
2/ Single-Unit Trucks - single frame trucks that have 2-Axes and at least 6 tires or a gross vehicle weight rating exceeding 10,000 lbs.
3/ Combination Truck – truck consisting of a separate power tractor coupled to at least one trailer
4/ Excluding motorcycles

Source: Automotive Insight, data from Federal Highway Administration Table VM-1 – Highway Statistics 2009

There were 10.97 million medium- and heavy-duty trucks on U.S. roads in 2009 and they traveled an average of 26,246 miles each. The larger combination (tractor-trailer) trucks average 64,132 miles annually. In addition, there were 842,000 buses that traveled an

¹⁵ Federal Highway Administration, U.S. DOT. Highway Statistics 2009. Retrieved November 15, 2011 from <http://www.fhwa.dot.gov/policyinformation/statistics/2009/vm1.cfm>

average of 17,052 miles each. This compares to average annual mileage of 11,218 miles for light duty vehicles. The truck fleet consumed an average of 4,053 gallons of fuel per vehicle (6.5 mpg), compared with 517 gallons per vehicle for light-duty vehicles (21.7 mpg). Fuel usage for combination (tractor-trailer) trucks was over 20 times that of light-duty vehicles, at 10,748 gallons per vehicle (6.0 mpg).

Potential Fuel Savings from Hybridization

Fitting hybrid powertrains to medium- and heavy-duty trucks can provide a much greater per-vehicle annual fuel savings than for light-duty hybrids. Present hybrid-electric powertrains can improve fuel economy by 20% to 50% over baseline gas or diesel engine powertrains. This represents a savings of 103 to 258 gallons per year for a light-duty vehicle, 391 to 978 gallons/year for a single-unit truck, and 2,150 to 5,374 gallons/year for a combination (tractor-trailer) truck as shown in the table below.

Table 4: Annual Fuel Savings Potential for Hybridization by Vehicle Type

Vehicle Type	Conventional Powertrain	Hybrid – 20% Fuel Savings	Hybrid – 50% Fuel Savings
	Fuel Use (gal/yr)	Fuel Saved (gal/yr)	Fuel Saved (gal/yr)
Light-duty Vehicle	517	103	258
Single-Unit Truck	1,956	391	978
Combination Truck	10,748	2,150	5,374

Source: Automotive Insight

The higher fuel savings potential for trucks can help to offset the significantly higher cost for a truck hybrid powertrain that results from the larger battery, traction motors, and other unique parts required. At the present diesel fuel price of approximately \$4.00 per gallon, a hybridized combination truck averaging just 20% improvement in fuel efficiency could save around \$8,600 per year in fuel cost.

2.2.3 Customer Benefits

Hybrid trucks and buses offer a wide range of customer benefits that can encourage demand, including significantly lower emissions, increased efficiency, and decreased maintenance costs.

- **Performance:** Hybrid trucks and buses typically exhibit performance levels comparable to their non-hybrid counterparts. Transit agencies report that acceleration in hybrid-electric buses is smoother and faster due to the increased low-end torque characteristics of electric motors. A hybrid truck can potentially increase its load carrying capacity if the powertrain is calibrated appropriately.
- **Fuel Efficiency:** Savings vary by truck or bus type and application. Eaton Corp. reports that MD package and delivery trucks with their HEV system typically average up to 30 percent fuel savings, while utility and telecomm trucks that need worksite power can see up to 60 percent savings by avoiding long idle periods. A National Renewable Energy Lab (NREL) evaluation of Orion VII hybrid transit buses vs. conventional diesel engine buses indicates that the hybrid buses provided a 37 percent average improvement in fuel economy.
- **Quieter Operation:** Hybrid technology can reduce noise through down-sized engines and “engine-off” periods during idle or at low speeds that result in silent running. Anecdotal evidence from hybrid bus drivers and passengers suggests that hybrid buses offer a quieter ride when compared to conventional diesel buses.
- **Maintenance Costs:** Hybrid trucks and buses have proven to have longer maintenance intervals with lower cost than conventional diesel engine vehicles. Brake life can be extended by 50 – 100 percent since deceleration is accomplished primarily through regeneration which conserves brake pads. By reducing reliance on the engine, hybrids can also potentially extend engine time in service between routine maintenance or overhauls. In addition, the electric drive typically has fewer parts, requiring less maintenance than a conventional transmission.¹⁶

These are benefits that can make hybrids attractive not only for commercial vehicles but also for military vehicle applications.

¹⁶ Technology & Maintenance Council (TMC). (2006). Hybrid Work Trucks: Preparing for Market Introduction, S.15 Specialty Trucks Study Group Information Report: 2006-2.

3.0 Truck and Bus Hybrid Powertrain Technology

Synopsis

Hybrid-electric powertrain technology for MD and HD trucks and buses is similar to that used in passenger hybrids, but requires larger components with higher power levels to handle the larger gross vehicle weights and unique duty cycles of these vehicles. Both parallel and series hybrid powertrains are in use in MD and HD trucks and buses. The Eaton HEV system uses a parallel hybrid architecture and is used widely in hybrid truck applications, while BAE Systems offers a series hybrid design that is typically used in transit buses. Allison Transmission produces a hybrid transmission for transit buses with a two-mode split parallel architecture having a pure mechanical path and a pure electrical path to achieve the highest energy efficiency. Meritor is also developing a truck hybrid system that has both parallel and series operating modes. The relatively low volume of many truck and bus designs has inhibited the development of hybrid models, since investment amortization can be difficult.

Storing sufficient electric energy on a hybrid truck or bus to meet the load and duty cycle requirements presents a particular challenge. Early hybrid buses actually used lead-acid batteries, and designs evolved to Nickel Metal Hydride or Nickel Cadmium cells when they became available. Most MD and HD hybrid vehicles today use Lithium-ion battery packs due to their greater specific energy and energy density, which helps to conserve size and weight on these heavy vehicles that must maximize load capacity. While lithium battery cost has declined somewhat in recent years, significant reductions are still required to make truck and bus hybrid powertrains cost-effective with broader customer appeal. Ultracapacitors have also been declining in price and are now being investigated for hybrid applications, possibly in a blended configuration with a battery pack to handle peak loads and allow a smaller battery.

Some trucks also have unique requirements for on-board or exportable power that can be addressed in the hybrid system, thus avoiding the need for a separate motor to drive hydraulic pumps or an auxiliary power unit. This has made plug-in hybrids particularly attractive for utility trucks with deployable booms or buckets. It is possible to size the battery pack(s) large enough to run the auxiliary equipment on these trucks for a full day without starting the engine, and then recharge the battery pack from an off-board power source at night.

3.1 The Challenge of Electrifying Medium- and Heavy-Duty Vehicles

There have been many light-duty hybrid-electric vehicle models introduced over the last decade, but development of hybrid powertrains for MD and HD trucks has been much slower. Passenger hybrid vehicles tend to span a fairly narrow weight range and operate on similar duty cycles, which allowed technology development to concentrate on similar size batteries, traction motors, power electronics, and controllers. However, MD and HD vehicles can span weight ranges much larger than that of a light duty hybrid, which requires a much greater range of technology development for hybridization. The low production volumes for individual truck and bus models also make it difficult for component manufacturers to amortize the investment in unique hybrid powertrain components for these vehicles.

Truck and Bus Duty Cycles

The duty cycles for MD and HD trucks and buses are very different from light-duty vehicles. A transit bus may average 750 start-stop cycles per day vs. just 30 for the typical passenger car. Accelerating one of these large, loaded vehicles from a stop requires an amount of power on a scale completely different than for a passenger vehicle. Once up to speed, however, the kinetic energy in this loaded vehicle makes it a good candidate for a hybrid system that can recover and store this energy during braking and reuse it on the next acceleration.

The GVW for a Class 8 truck can range up to 20 times that for a passenger vehicle. While it could be expected that the components to hybridize such a vehicle might also need to be many times larger, the traction motors and battery packs required for a medium-duty diesel-electric hybrid truck can actually be similar in size to those used in a light-duty full-electric vehicle. The engines in large trucks are not scaled up in proportion to the GVW, and the resulting power-to-weight ratio in these heavy vehicles is much lower than in passenger vehicles. The difference is partially compensated for with transmissions having more gears in order to multiply the engine power for greater tractive effort. The remaining difference shows up in much slower acceleration times. A hybrid powertrain simply needs to provide equivalent performance to these existing truck powertrains to meet customer requirements.

The selection of the hybrid system configuration depends more on the intended truck application and duty cycle than it does the maximum vehicle weight. The relatively low speed operation and frequent stop-and-go driving patterns for urban buses have led to frequent use of series hybrid configurations in these vehicles. In some cases the conventional diesel engines have been replaced with micro-turbines that can run the

series hybrid generator set within a narrow speed range for greatest efficiency. A plug-in hybrid configuration is desirable in a vehicle that needs on-board power to operate equipment while stationary (utility bucket truck), but may not make as much sense in a vehicle that records high daily mileage or cannot be recharged easily.

Diverse Configurations and Uses

One of the challenges in electrifying truck and bus powertrains is that there are so many different configurations, weights, uses, and duty cycles for these vehicles that a wide range of technical solutions may be required to meet all of the operational demands. Eaton Corporation, a leader in the development of truck hybrid-electric powertrains, has documented the wide potential range of energy storage requirements, electric motor power and torque, and other factors required to satisfy the full range of MD and HD hybrid trucks and buses in the figure below.

<u>Potential Range</u>	
	<ul style="list-style-type: none"> • Energy Storage: 2 – 20 kWh • Power: 20 – 80 kW • Torque: 200 – 1000 Nm
	<ul style="list-style-type: none"> • EV mode: None – 10 mile range • IC engine: Diesel, Gasoline, NG • Electrification: None – full
	<ul style="list-style-type: none"> • Plug-in: Yes – no • Export power: Yes – no
	<ul style="list-style-type: none"> • Other unique requirements <ul style="list-style-type: none"> • Emergency power, anti-idle, reefer, etc
	
	
	
	
	
	
	
	

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Figure 2: Many Hybrid Truck and Bus Applications With Divergent Needs

Source: Cornils, Helene – Eaton Corp. (June 10, 2009). Hybrid Solutions for MD Commercial Vehicles. Retrieved from <http://www.erc.wisc.edu/documents/symp09-Cornils.pdf>

Low Volumes

Most passenger cars are designed for high volume manufacture, with perhaps two engine choices that are intended to accommodate the full range of users. Medium- and heavy-duty trucks come in a vast array of configurations, most of which are manufactured in very low volumes, sometimes even specified to the needs of a single fleet user. There can be five or six engine options, plus choices in transmission and final drive ratios to meet the expected GVW and the customer's duty cycle requirements. There is typically a wide range of wheelbases and body options, making it difficult to package the components needed for hybridization in standard locations across the many truck configurations.

Since individual model commercial truck and bus volumes are much lower than for light duty vehicles, it is difficult to achieve the economies of scale needed to recover investment in the required components. This makes it advantageous for key electrification components such as batteries, traction motors, and controllers to be shared among multiple applications. This is already starting to show up in battery applications, with the JCI 14 kWh Li-ion battery pack being used by multiple manufacturers such as Azure Dynamics and Odyne in a variety of truck applications. The Remy HVH250 traction motor used in the Odyne hybrid is also a proven unit that has been utilized in other hybrid bus systems.

This component sharing is also happening at the battery cell module level. According to a recent article in SAE Truck and Bus Engineering Online, "A123 Systems has signed a production agreement with Smith Electric Vehicles to supply battery modules for Smith's lineup of zero-emission, all-electric commercial vehicles (CVs). A123 expects to begin shipping its 5 kWh, automotive-class prismatic modules to Smith for integration into battery packs in the second half of 2011. Plans call for the battery technology to be first implemented in the Smith Newton truck, an all-electric, 7.5-ton (16,535 GVWR) to 15-ton (33,000 GVWR) vehicle that has been commercialized globally. Smith's customers include Frito-Lay (a division of PepsiCo), Staples, and Coca-Cola, as well as the U.S. Marine Corps. 'The highly scalable, building-block design of A123's modules enables us to build customized battery packs to meet individual customers' range specifications,' said Bryan Hansel, President and CEO of Smith Electric Vehicles."¹⁷

One factor that helps offset the effect of low volumes for individual truck models is the fact that a single truck chassis design is usually shared between many end-user configurations, with different bodies added by either the truck manufacturer or

¹⁷Gehm, Ryan, SAE Truck & Bus Engineering Online. (May 11, 2011). A123 to supply Smith with battery modules for all-electric CVs

specialty body builders. Once the truck manufacturer produces a hybridized chassis, it can then lead to many new hybrid truck models.

The truck and bus industry is also accustomed to using engines, transmissions, and drivelines from a variety of manufacturers. The low sales volume of individual truck models has encouraged the sharing of hybrid systems and components, particularly in the early stages of this new truck technology, in order to achieve some economies of scale. As a result, hybrid powertrain systems developed by a few companies such as Eaton Corp. and Allison Transmission have been utilized by many truck and bus manufacturers, with the key variable being the engine supplied by the truck or bus manufacturer.

Lack of Supporting Systems

Another factor that has inhibited the introduction of MD and HD hybrid trucks has been the lack of commercially available electrified accessories such as steering, braking, and heating/cooling systems that are needed for a hybrid vehicle. During engine-off periods in a hybrid, the accessories traditionally driven by the engine must be powered in some other manner to preserve functionality.

- Electric-assist steering systems were used only in small cars a decade ago due to torque limitations. New, higher torque designs have been developed, partly in response to the hybridization of a wide range of LD vehicles, and electric-assist steering can now be found in vehicles up to light-duty pickups such as the Ford F-150. These still will not work in MD and HD trucks, however, and the typical approach is to power the hydraulic steering pump with an electric motor, which can add weight.
- Brake systems must be modified to withhold friction braking during regeneration in order to obtain maximum energy recapture. Brake manufacturers have developed electro-hydraulic brake systems for light-duty vehicles that are used in all but micro- and mild hybrids. These have a pedal stroke sensor to measure brake demand and a brake controller that communicates with the powertrain controller to synchronize regeneration. HD trucks and buses typically use air assisted brakes, and new brake designs must similarly be developed to optimize regeneration in a hybrid truck.
- Heating and cooling a hybrid vehicle during engine-off operation has required the development of electric water pumps and cost-effective electric air conditioning compressors. The volumes of light duty hybrids have again made

this worthwhile for the manufacturers of these systems, but additional work is needed to provide similar designs for MD and HD trucks.

One approach to this accessory issue used by Azure Dynamics in their medium-duty hybrid system is to add a decoupling clutch to the front accessory drive so the integrated starter-generator (ISG) motor mounted there to restart the engine can also be activated to drive the accessories through the belt when the engine is off.

Manufacturer Plans

Now that the customer interest in hybrids has been established and truck and bus entries are multiplying, some truck companies such as Daimler are developing their own heavy truck hybrid systems. Other companies are developing new types of hybrid powertrains (e.g. Meritor Dual-Mode system) that can better meet the full range of truck duty cycle requirements. There is also rapid development occurring in the other vehicle systems that must be electrified to support hybrid functionality with engine-off operation. Suppliers had been reluctant to invest in the required designs until hybrid truck viability was proven.

One area of opportunity for further fuel efficiency gains is to optimize truck engines for hybrid system operation, as there has been little work done on this to date. In fact, many truck hybrids have utilized the carryover, non-hybrid engine configuration whereas light duty gas-engine hybrids typically have the engine downsized and in some cases, converted to Atkinson-cycle operation for further efficiencies. Some of the delivery fleet operators surveyed for this study indicated that they would like to see engine displacement reduced in their hybrid truck models. The commonly used motor in the Eaton hybrid system produces nearly 60 hp (44 kW) peak power, so a truck that normally utilizes a 200 hp (148 kW) diesel engine might have displacement reduced by 30% to be better matched with the power from the electric motor.

Unique Class 8 Vehicle Hybrid Challenges

Class 8 vehicles have GVWs starting at 33,000 lb, and can range up to 150,000 lb for some models. They can span a wide range of configurations and duty cycles, from refuse haulers to semi-tractors and urban buses. The extreme weights and varied uses make it more difficult to develop hybrid drivetrains that will meet the needs of multiple users.

In a February, 2010 SAE presentation entitled “Class 8 Electric Hybrids – Opportunities and Challenges”, Brad Hicks of ArvinMeritor (now Meritor) defined the following challenges for the hybridization of Class 8 vehicles.¹⁸

- Not All Duty Cycles Lend Themselves to Hybridization
- Industrialization of Robust, Electrical Components
 - “Chicken and Egg” regarding Sales Volumes
- Size and Weight of E-Machines
 - Power Density Dependent Upon Cooling Capabilities
- Business Case
 - Most Fleets Require 3 year payback or less
 - Currently may be dependent upon Government Incentives
 - Fuel Prices – Huge Variable
 - Battery Costs – Huge Variable
- Batteries
 - High Cost
 - Currently at \$1000-1200 per kW-hr
 - Objective: \$300-500 kW-hr
 - High Weight and Size
 - Energy Density of Li-Ion Batteries ~ 10% of Diesel fuel
 - Durability
 - For Class 8, Require up to 3000 full cycles
 - Need 7 years of Life
 - Replacement compromises business case
 - Battery Condition
 - Predicting Battery Life
 - State of Charge Determination

Truck and hybrid drivetrain manufacturers are responding to these challenges, and Class 8 hybrid trucks are now coming into the market.

¹⁸ Hicks, Brad, ArvinMeritor. (February 8, 2010). Class 8 Electric Hybrids – Opportunities and Challenges. SAE Hybrid Vehicle Technologies 2010 Symposium.

3.2 Diesel – Electric Hybrid Architectures

A hybrid electric vehicle combines power from a combustion power source and an electric power source to deliver propulsion at the drive wheels. There are three primary types of hybrid electric powertrain systems presently being utilized in MD and HD vehicles:

- **Hybrid electric:** Charge-sustaining hybrid electric vehicles (HEVs) generate all their power on board, and deliver that power to the wheels either in parallel with an internal combustion engine (ICE) or in series with no connection between the engine and the wheels. Some HEV buses have also been produced with gas turbines as the primary power source rather than a combustion engine.
- **Plug-in hybrid electric:** Plug-in hybrid electric vehicle (PHEV) systems store electric power in a battery pack that is replenished from an off-vehicle source. They typically utilize this power to drive the vehicle in electric-only mode for some distance before the ICE is actuated to provide additional range or charge the battery. The ICE power can be transmitted through either a parallel or series configuration.
- **Mild electric power take-off (EPTO) hybrids:** These systems typically do not provide any power to the wheels from electricity; rather, they power all PTO equipment via battery storage. As a result, these vehicles do not require the ICE to idle for extended periods during equipment usage. Some manufacturers offer an EPTO option along with a full HEV powertrain.

This report focuses on these three electric hybrid system configurations with the primary power source being a diesel fuel ICE. Most MD and HD trucks utilize diesel engines rather than gasoline due to their superior torque output and fuel efficiency when handling the large vehicle weights and loads typically encountered in these vehicles.

3.2.1 Parallel vs. Series Configuration

HEV's are characterized by the way in which power is supplied to the drivetrain, normally in either a Series or a Parallel configuration.

A **Series hybrid-electric** powertrain has no direct, mechanical path between the engine and the drive wheels. The internal combustion engine (ICE) is coupled to an electric generator that supplies electricity to the traction motor/generator to propel the vehicle, and to the energy storage system when it needs to be recharged.

- One of the main advantages of a series HEV is that the engine and vehicle speeds are decoupled. As a consequence, the engine can run at its optimum speed to reduce fuel consumption.
- However, as the electric machine is the only drive mechanism connected to the wheels and the engine/generator set is sized for sustained gradeability, this configuration requires a relatively large energy storage system (battery pack), and electric machine, which can add inefficiencies and weight.

A **Parallel hybrid-electric** powertrain has mechanical connections to the wheels from both the electric machine and the combustion engine. Because of this, both devices can provide power during accelerations and it is possible to downsize both the engine and the electric machine compared to a series hybrid.

- If the electric machine is large enough, the vehicle can be launched on electric power alone if there is a way to decouple the engine from the drivetrain.
- The engine speed is linked to the vehicle speed, so the engine can operate close to its best efficiency curve only under certain conditions.
- Since both mechanical and electrical energies can be used to directly propel the vehicle, the powertrain efficiency is increased compared to a series hybrid configuration during most operating conditions.

The power sources and flow paths for Series and Parallel hybrid architectures are contrasted in the figures below.

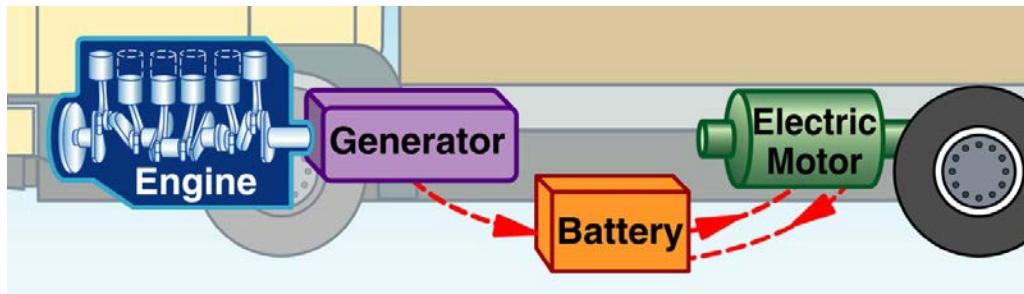


Figure 3: Series Hybrid Powertrain Configuration

Source: Southwest Research Institute

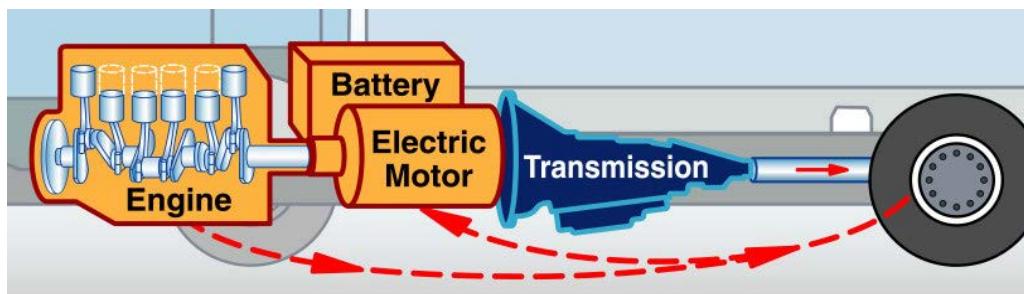


Figure 4: Parallel Hybrid Powertrain Configuration

Source: Southwest Research Institute

An additional distinction for a parallel hybrid configuration that is often made in medium- and heavy-duty vehicle applications is whether it is a pre-transmission or post-transmission hybrid drivetrain.

In a **Post-Transmission Parallel Hybrid**, the motor/generator is mounted along the driveshaft behind the transmission. The electric motor and combustion engine work in parallel to drive the wheels during acceleration, and the motor's field can be reversed to generate electricity to recharge the batteries during deceleration.

Advantages of this design include:

- Drop-in installation makes this architecture simple to integrate into the OEM production line or retrofit into an existing vehicle
- Little or no vehicle modification
- Emissions recertification may not be required
- Redundant power sources mean that the vehicle will continue to operate if the electric motor fails — key for vehicles that require additional safety features

The post-transmission hybrid architecture is illustrated in the figure below.

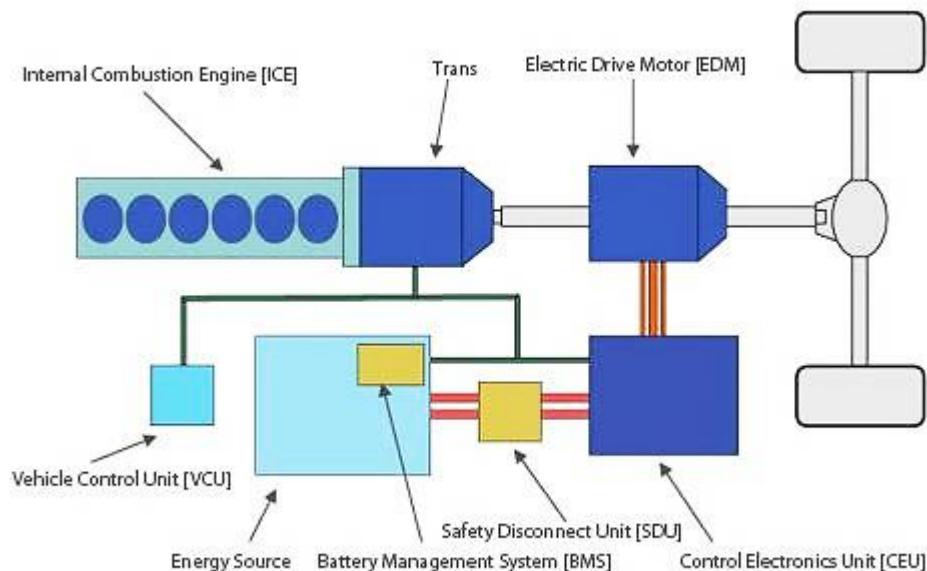


Figure 5: Post-Transmission Parallel Hybrid Architecture

Source: Enova Systems website. Retrieved Dec. 5, 2012 from
<http://www.enovasystems.com/drive-system-architectures.html>

In a **Pre-Transmission Parallel Hybrid**, the electric motor/generator is located between the engine and the transmission. This architecture optimizes the performance of both the electric motor and the combustion engine by having them work in tandem with the combined power going through the transmission. As with the post-transmission design, the electric motor field is reversed to generate electricity that recharges the batteries when the vehicle slows.

Advantages of this design include:

- Greater efficiencies than for a post-transmission design, since there is no transfer of energy down the drive shaft
- The motor power and torque can be multiplied by the transmission gearing
- Possible to integrate with an existing OEM transmission, saving the cost of procuring a new transmission
- Ideal for OEM vehicles built from the ground up

The pre-transmission parallel hybrid architecture is illustrated in the figure below.

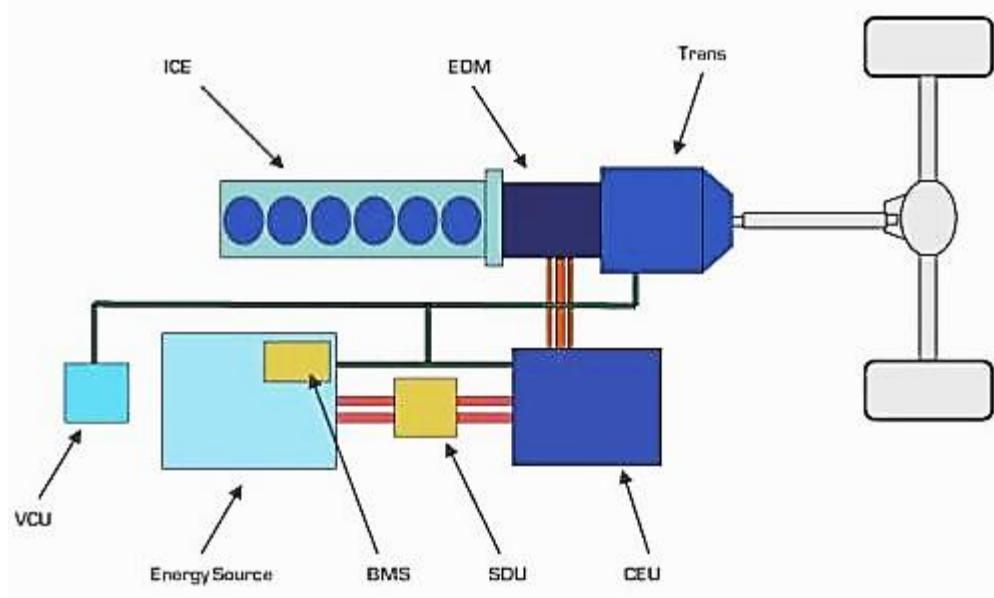


Figure 6: Pre-Transmission Parallel Hybrid Architecture

Source: Enova Systems website. Retrieved Dec. 5, 2012 from
<http://www.enovasystems.com/drive-system-architectures.html>

The most common hybrid system being used in medium- and heavy-duty trucks today is a pre-transmission parallel hybrid design produced by Eaton Corporation. Additional details on this system can be found in Section 4.2.4.

A Power-split hybrid-electric combines aspects of both series and parallel hybrids. The engine power is divided along two paths inside the transmission: one goes to the generator to produce electricity that can either recharge the battery or drive the traction motor, and the other goes through a mechanical linkage to drive the wheels.

Since the engine, generator and motor speeds are decoupled, the efficiency of each can be maximized at any vehicle operating point. In light-duty, FWD hybrid vehicles from Toyota and Ford, a planetary transaxle is used to accomplish this power-split mechanism with the generator load used to control the engine and motor speeds. This architecture is illustrated in the figure below.

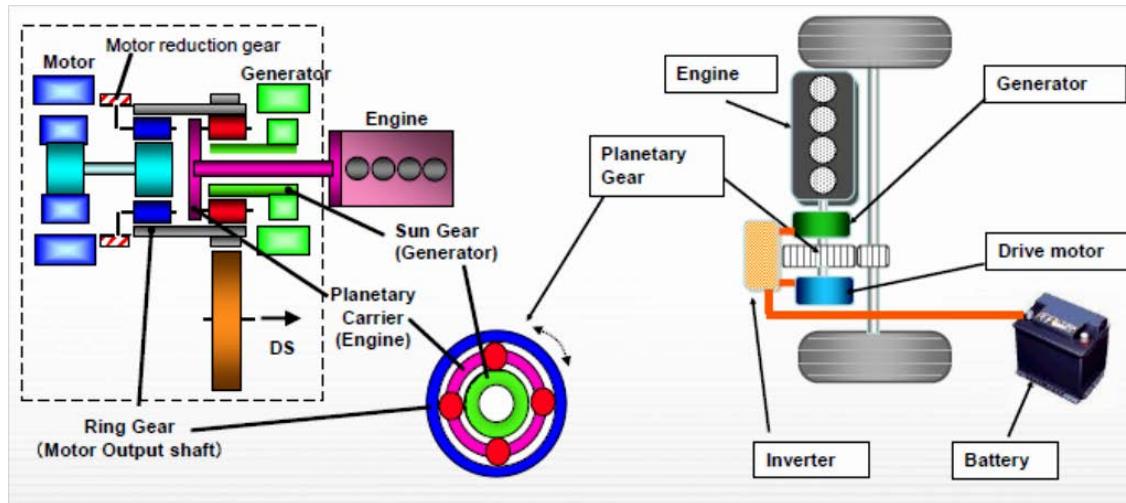


Figure 7: Planetary Type Power-Split Parallel-Series Full Hybrid

Source: Thunes, Owen, Nissan NA. Powertrain Electrification. SAE Seminar: Adjusting Drivetrain Design for EVs and Hybrids, Dec 7, 2011.

There are also RWD hybrid transmission designs that blend parallel and series power paths. The Two-Mode hybrid architecture developed by GM, DaimlerChrysler and BMW in a consortium is also a power-split design with two electric machines and two planetary gear sets plus coupling clutches. GM's Allison Transmission division is now producing the Allison Hybrid EP transmission for transit buses that is based on this same design. It features a two-mode split parallel architecture with a pure mechanical path and a pure electrical path to achieve the highest energy efficiency. Additional details can be found in Section 4.2.5.

Meritor is also developing a diesel-electric hybrid system for Class 8 trucks that is similar to a Power-split design in that it combines Parallel and Series Hybrid design elements. Meritor calls this a Multi-Mode Hybrid (formerly Dual Mode). Additional details on this system can be found in Section 4.2.7.

3.2.2 Fully Integrated vs. Through-the-Road Hybrids

A fully integrated hybrid combines the electric drive motor into the power flow path between the engine and drive wheels in either a parallel or series configuration, as described above. A through-the-road (TTR) hybrid is another architecture where the electric drive mechanism acts separately from the ICE drivetrain. This is typically done by having the combustion engine and transmission provide driving force to one axle while a traction motor acts on another. There is no physical connection between the axles or the engine and motor. The two are coupled only through the road, and controlled and coordinated by electronic controls that respond to changes in the traction at each axle. The motor is capable of regenerative energy recapture.

The system diagram for a TTR hybrid is shown in the figure below. In this case, the engine drives the front wheels through the conventional transmission while a motor/generator is added to the rear axle for added drive force and power regeneration. A decoupling clutch is used to allow engine-off operation while an integrated starter/generator (ISG) in the engine accessory drive handles restarting the engine and can add to power regeneration of the battery.

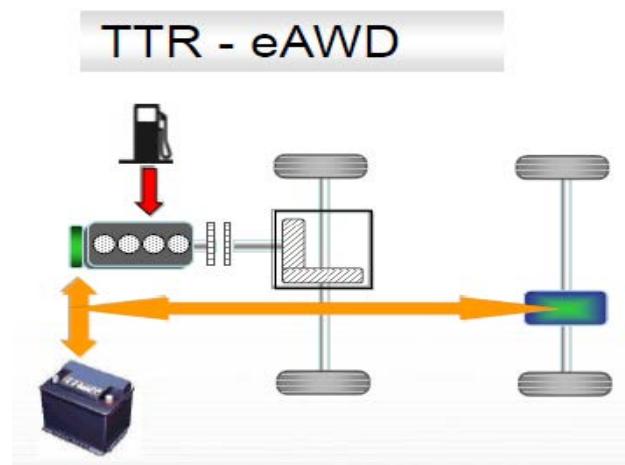


Figure 8: TTR Hybrid with ISG for Engine-Off Operation

Source: Thunes, Owen, Nissan NA. Powertrain Electrification. SAE Seminar: Adjusting Drivetrain Design for EVs and Hybrids, Dec 7, 2011.

The TTR hybrid architecture is particularly well suited for retrofit applications, since there is no mechanical change needed to the primary powertrain elements. Unless the engine is downsized, however, the maximum fuel efficiency benefits of hybridization may not be achieved.

3.2.3 Plug-in vs. Charge Sustaining Hybrid Systems

A **Plug-in Hybrid Electric Vehicle (PHEV)** is a hybrid that is capable of having the battery restored to full charge by an external electric power source when the vehicle is parked, in addition to on-board charging by the combustion engine powering a generator. The battery is normally larger than that in a conventional full hybrid in order to offer additional range on the electric motor alone.

As with conventional HEVs, a PHEV can employ either a series or parallel architecture, and the parallel type can also utilize a powersplit mechanism which combines elements of both.

- A **series PHEV** is basically a battery-electric vehicle (BEV) with a small combustion engine powering a generator to provide electric power for additional range when the battery charge is depleted.
 - There is no direct mechanical connection between the engine and drive wheels, which means the engine can be designed to run at its most efficient speed when powering the generator.
 - Microturbines running on diesel fuel or propane have been used in some series PHEV transit buses to power the on-board generator.
- A **parallel PHEV** can simultaneously transmit power to the drive wheels from both the combustion engine and a battery-powered electric motor. The power paths can be separate (in some cases acting on opposite axles), or blended through a powersplit or other mechanism.
 - Parallel PHEVs, like conventional HEVs, can be programmed to use the electric motor to substitute for the ICE at lower power demands and to substantially increase the power available to a smaller ICE than would normally be used.
 - Unlike HEVs, they will normally have a significantly greater all-electric range before the engine needs to turn on.

Although the larger battery pack required for a PHEV can be a significant cost barrier, this technology has been used in transit buses for the last 15 – 20 years. Ebus Inc. has produced series PHEV transit buses that utilize a diesel-powered microturbine to drive the on-board generator and provide additional range once the primary charge in the battery pack is depleted. Others have proposed installing a rapid charge station along the bus route to recharge the batteries on a PHEV bus for additional electric range. Proterra has developed such a system for a pure-electric bus that it produces. The bus connects with a quick-charge mechanism at a layover point and the battery is recharged at high current in six to ten minutes. A similar approach might be employed with a parallel PHEV bus where there is still a need for engine power. If the battery size and

charging time were configured appropriately, the hybrid bus could be operated on electric drive power the majority of the time with the diesel engine available for additional power as needed.

PHEV hybrid designs are now starting to appear in medium-duty truck applications as well. In some cases, the battery pack is used primarily to power an electric motor which drives on-board hydraulic pumps and accessories that previously had to be powered by the truck's engine while idling. The same motor can be connected through the power take-off (PTO) to the truck's conventional transmission to augment the engine while driving to and from the jobsite, and also provide a power path to regenerate power to the battery under deceleration and braking.

Odyne has recently introduced this type of PHEV powertrain in a standard chassis-cab platform that is aimed at a variety of work trucks over 14,000 lb GVW such as bucket trucks and digger derricks in utility fleets. Additional details can be found in Section 4.2.8.

Azure Dynamics is also bringing PHEV powertrains to market for both the Ford E-Series and F-Series truck chassis. Additional detail can be found in Section 4.2.2.

3.2.4 Range of Hybridization from Start-stop Through Full Hybrids

As for light duty vehicles, hybrid powertrains for MD and HD trucks are characterized by the amount of electric power delivered to supplement the primary diesel ICE engine power. However, the operating voltages for each level of hybridization can be significantly higher for the MD and HD trucks since the total power output is also much higher.

- The **Micro-hybrid**, or Stop-Start system, shuts off the engine when the vehicle is at rest in order to save fuel, and automatically restarts it when acceleration is requested by the driver. This is typically accomplished through a Belt Alternator Starter (BAS) mounted in the front accessory drive that is powerful enough to restart the engine using the accessory drive belt. Fuel economy improvement is typically in the range of 3 – 6%.

This technology is expected to find much greater application in light-duty vehicles in North America over the next five years, and may spread to MD and HD vehicles as well.

- A **Mild hybrid** includes an electric motor/generator that can assist the ICE under acceleration and regenerate energy into the battery pack during deceleration, but does not have enough power to propel the vehicle on its own. Mild hybrids typically achieve fuel consumption savings of 8 to 12 percent.
- A **Full hybrid** vehicle is capable of starting up and running on the electric traction motor alone up to a certain speed or distance before the ICE engages. This is limited by the amount of electric power that can be stored and deployed, so a full hybrid MD or HD truck can require a significantly larger traction motor and battery pack than in a LD vehicle.

Full hybrids can achieve fuel economy improvements of 30-50% or greater, depending on duty cycle, with the largest improvement occurring in city driving. They are more likely to have electrified accessories such as power steering and air conditioning due to the extended engine-off operating modes.

3.3 Energy Storage Systems for Hybrid Regeneration

Synopsis

Unique challenges exist for the application of electrical energy storage components in medium- and heavy-duty hybrid trucks, including batteries and ultracapacitors. Light-duty HEVs and EVs focus on energy capacity for long battery range, or rapid power charging and discharging capabilities for acceleration and braking energy recovery, or a combination of both. Heavy-duty vehicles require much higher power levels for all-electric operation, plus greater capability for charge rate and level of charge acceptance to maximize the recapture of braking energy.

Vehicle manufacturers are focusing on hybrid powertrains based on diesel-electric architectures that require batteries with high power capability to assist in vehicle acceleration, rapid charging, and efficient recovery of braking energy. Various Lithium-ion battery types are now replacing early applications of lead-acid and nickel-metal hydride (Ni-MH) batteries in hybrid trucks and transit buses. The energy storage system accounts for about one-third of the hybrid system cost in a heavy-duty vehicle. As with light-duty hybrids, battery cost remains a key inhibitor to wide-spread technology adoption.

3.3.1 Unique Storage Requirements for Trucks and Buses

The main purpose of energy storage in a hybrid-electric vehicle is to provide electricity to the traction motor for motive power and to capture regenerative braking energy. The first generations of hybrid-electric buses employed lead-acid batteries followed by either nickel-cadmium (NiCd) or nickel-metal hydride (NiMH) batteries. More recent offerings have begun to use lithium-ion (Li-ion) batteries which offer increased energy density, thus providing the same energy storage at equal or lower weight plus longer cycle life.

The electrification of heavy transportation vehicles places particular demands on the energy storage devices: they must be very robust and reliable with a long life and low maintenance requirements. They must be able to operate efficiently under harsh conditions, and deliver high peak currents. They must also be able to work on a high duty cycle and cope with frequent deep discharging. Finally, they must be straightforward to integrate into a vehicle design.

The high vehicle mass and inertia for heavy-duty trucks and buses requires a much greater capability for charge rate and level of charge acceptance to maximize the recapture of braking energy. Battery packs must be significantly larger than for light-duty HEVs and EVs, and advancements in cell chemistry are required to improve charge flow capabilities. This requirement has provided an opportunity for the use of ultracapacitors to augment chemical batteries for greater power flow capabilities. It also means that heavy trucks and buses are less practical as battery-only EVs due to the required battery size for reasonable performance.

3.3.2 Batteries for Heavy-Duty Vehicles

The specific power of a battery is very important for HEV and EV applications. In contrast to specific energy, which is a material property, specific power depends strongly on factors like electrode thickness and the size of electrode particles, which may be controlled in the manufacturing process. Manufacturers have developed sophisticated proprietary manufacturing techniques, such as coating electrode particles with other materials that are more conductive, in order to increase the power density of their batteries.

A 40,000 lb transit bus with a series hybrid-electric drivetrain can require a battery pack rated at up to 15 kWh and 200 kW peak power vs. around 1.5 kWh and 30 kW peak power for a passenger car hybrid battery. The typical operating voltage for the transit bus system is 600 volts DC with 333 amp current vs. around 300 volts DC with 110 amp current in the passenger hybrid. Due to the much higher number of start-stop cycles on the transit bus, the energy throughput per day can be 375 kWh vs. just 3 kWh for the passenger hybrid. This means that battery packs need to be designed for 50,000 lifetime energy storage cycles in a hybrid transit bus vs. just 3,600 cycles in the typical passenger hybrid.

These energy storage requirements are summarized in the table below from ISE Corporation.

Table 5: Energy Storage System Requirements for Transit Bus vs. Passenger Car Hybrids

COMPARING ENERGY STORAGE REQUIREMENTS: AUTOMOTIVE & HEAVY-DUTY TRANSIT

MEASUREMENT	PASSENGER CAR	TRANSIT BUS
Typical vehicle curb weight	3,500 pounds	40,000 pounds
Battery (B)/Ultracapacitor (U) ESS capacity	~ 1.5 kWh	B: 15 kWh / U: 1.0 kWh
Vehicle to ESS weight ratio	20	30
Start-stops per day	30	750
Energy per cycle	100 Wh	500 Wh
ESS peak power	30 kW	200 kW
Typical ESS voltage/current	273 VDC/110A	600 VDC/333A
Energy throughput per day	3 kWh	375 kWh
Daily equivalent full ESS cycles	1	B: ~ 15 / U: ~ 200
Lifetime equivalent full ESS cycles	3,600	B: 50,000 / U: 700,000

Performance numbers are estimates derived from actual fleet data, assuming 300 days of operation a year for 12 years.

Source: ISE Corporation brochure – ISE CORP PROVIDES THE SMART CHOICE FOR HEAVY-DUTY ENERGY STORAGE SYSTEMS

Batteries are rated in terms of both their peak power in kilowatts (kW) and their energy capacity in kilowatt-hours (kWh). The wide range of MD and HD truck and bus types and applications requires a variety of battery power and energy capabilities. A Class 4 Package and Delivery vehicle with a parallel hybrid system needs around 35 kW and 1.5 kWh, while a Class 7 beverage tractor might require 65 kW and 2.5 kWh. A utility truck that needs engine-off equipment power will require a battery with more energy capacity, on the order of 10 kWh at 50 kW power, while a heavy transit bus or Class 8 truck may need up to 90 kW power with 4.0 kWh energy capacity. Note that these power and energy levels are lower than for the series hybrid bus discussed above which requires additional energy storage capacity. These varying battery requirements for parallel hybrid systems in trucks and buses are illustrated in the figure below.

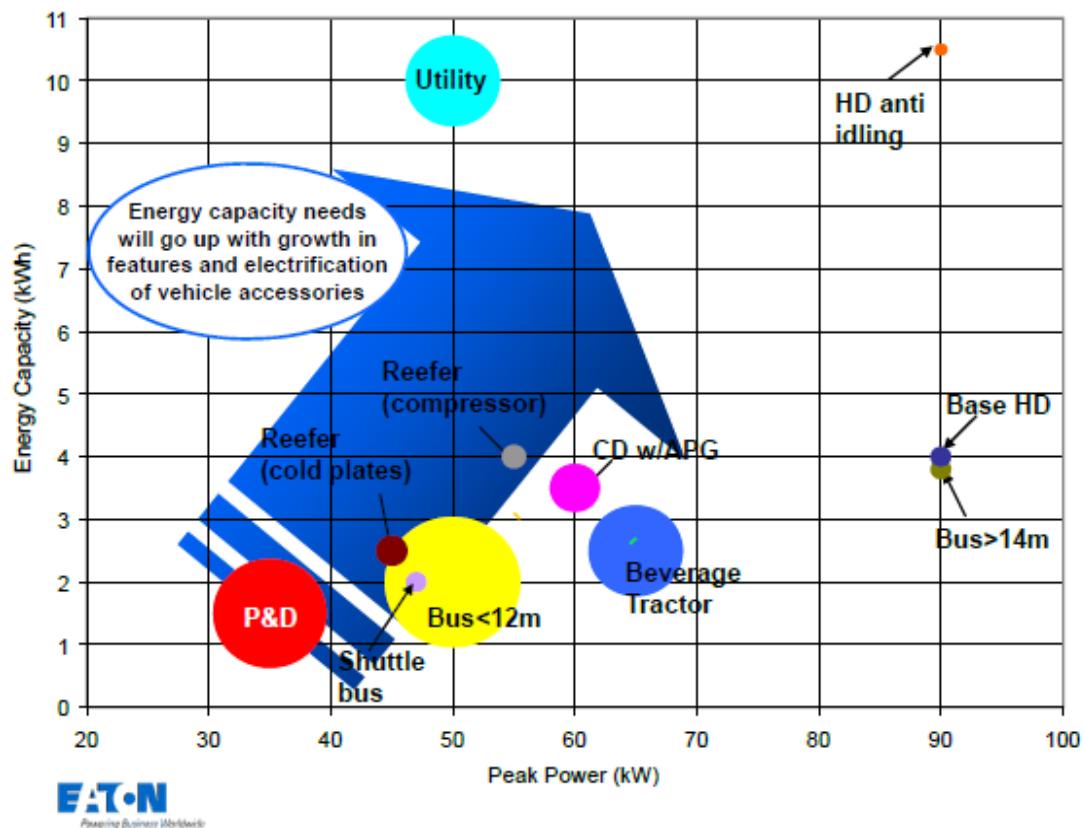


Figure 9: Battery Power and Energy Needs for Different Electrified Truck and Bus Types

Source: Cornils, Helene – Eaton Corp. (June 10, 2009). Hybrid Solutions for MD Commercial Vehicles. Retrieved from <http://www.erc.wisc.edu/documents/symp09-Cornils.pdf>

3.3.3 Ultracapacitors for Heavy-Duty Vehicles

Ultracapacitors are becoming more widely accepted in the energy storage industry in both standalone applications and in combination with batteries. The ultracapacitor's very low internal resistance permits it to deliver and absorb high energy currents, whereas the higher internal resistance of a traditional chemical battery prohibits this. Today's ultracapacitors can have power densities of up to 20kW/kg. While a battery generally demands a long recharging period, ultracapacitors can recharge very quickly.

They also retain their ability to hold a charge, even after multiple recharging, much longer than do traditional batteries.¹⁹

Ultracapacitors can have much higher power density than chemical batteries but significantly lower energy density, as shown in the Ragone plot depicted in the figure below for various battery and ultracapacitor types.

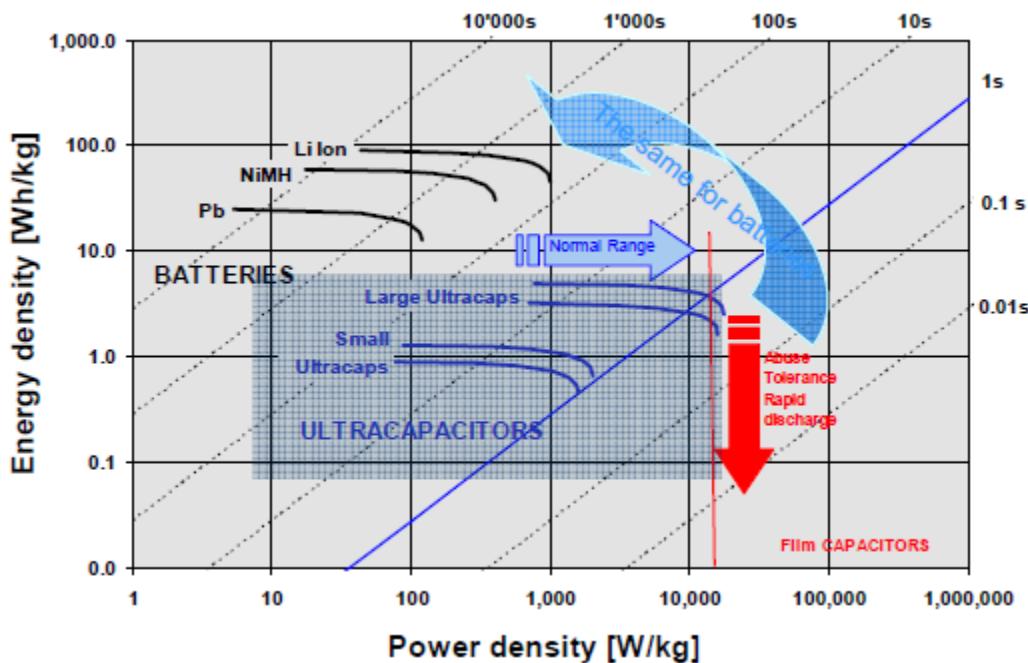


Figure 10: Power vs. Energy Density for Batteries vs. Ultracapacitors

Source: Miller, Dr. John M., Maxwell technologies. Energy Storage Technology, Markets and Applications, Ultracapacitors in Combination with Lithium-ion.

A key consideration in determining the applicability of ultracapacitors for a particular vehicle application is the proper assessment of the energy storage and power requirements. The energy storage requirements vary a great deal depending on the type and size of the vehicle being designed and the characteristics of the electric powertrain to be used. The cost of the ultracapacitors can be competitive with lithium-ion batteries for high volume production and carbon prices of less than \$20/kg.

¹⁹ What are Ultracapacitors? Retrieved November 21, 2011 from <http://ultracapacitor.net/whatareultracapacitors.php>

Ultracapacitors are beginning to be applied to hybrid-electric energy storage systems in transit buses and commercial trucks. The company most active in developing such systems has been ISE Corporation (now BLUWAYS).²⁰ ISE Corp. has developed a 360V ultracapacitor unit consisting of 144 Maxwell 2600F cells connected in series, as shown in the figure below. The weight and volume are 114 kg and 189L, respectively. The unit stores 0.325 kWh of energy (0.245 kWh useable).



Nominal Voltage	360V*
Peak Voltage	403V**
Rated Current	400A
Capacitance	18.05F
Total Energy Stored nominal / max.	0.325kWh / 0.407kWh
Leakage Current	5mA nominal
Operating Temperature	-35 to 65 °C
Weight	240lbs
Dimensions wxlxh	24"x40"x12"
Standard Pack	144 Capacitors
Fire Suppression System	Heat Activated Halotron System

Figure 11: The ISE ECC Ultracapacitor Unit (360V, 0.325 kWh)

Source: Bartley T. Ultracapacitor Energy Storage in Heavy-duty Hybrid Drive Update.

In a transit bus, two of these units are used in series resulting in a voltage of 720V and energy storage of 0.650 kWh. The peak power capability of the combined unit is over

²⁰ Bartley T. (July, 2005). Ultracapacitor Energy Storage in Heavy-duty Hybrid Drive Update. Proceedings of the Advanced Capacitor World Summit 2005. San Diego, California.

300 kW. ISE utilizes this EDLC unit with a 225 kW electric motor in series hybrids using either gasoline or diesel engines or hydrogen fuel cells. Since the capacitor unit stores only about 0.5 kWh, it can provide power only during vehicle acceleration and recover energy during braking. The engine or fuel cell must provide all the power during cruise and when climbing grades.

ISE has built over 100 buses using the EDLC energy storage units for transit companies in Southern California. The buses are in daily revenue service. Fuel economy records indicate that the hybrid buses using ultracapacitors achieve 25-30 % better fuel economy than the diesel powered buses and consistently better fuel economy than hybrid buses using batteries. The measured round-trip efficiency of the ultracapacitor unit was 94%.²¹

Maxwell Technologies is also producing ultracapacitor modules aimed at transportation applications, from light-duty hybrids to heavy truck, transit buses, rail, and off-road vehicles. Maxwell's 48 Volt and 125 Volt HTM BOOSTCAP® ultracapacitor modules allow ultracapacitor-based braking energy recuperation and torque assist systems in transportation applications. Both modules are based around 2.7V BOOSTCAP MC3000 Power cells rated at 3,000F which have a very low internal resistance, which results in excellent efficiency during charging and discharging. Up to 12 of the 125V HTM modules may be linked in series to deliver a total of us much as 1,500V. Balancing interconnectivity between modules is fully integrated within the module and requires no additional hardware, to help with system design.



Figure 12: Maxwell 48V and 125V Transportation Ultracapacitor Modules

Source: Maxwell technologies website: <http://www.maxwell.com/products/ultracapacitors/>

²¹ King RD. etc. (April, 2005). Performance and Emissions Test Results of a Low-floor, Low-emissions Transit Bus with a 225 kW Hybrid –Electric Propulsion System. EVS-21, Monaco.

There are three sizes of 48V Maxwell ultracapacitor modules ranging from 61 – 77 Amps maximum continuous current and 1,100 – 1,900 Amps peak current. The 125V module is rated at 140A continuous current and 1,800A peak current. The largest 48V module provides 52.8 Wh stored energy and weighs just 13.5 kg, while the 125V module provides 136.7 Wh and weighs 60.5 kg.²²

3.3.4 Blended Systems and Other Energy Storage Mechanisms

Electrified trucks and buses require high peak charge and discharge currents as a result of their high mass and inertia, which are difficult to deliver with chemical batteries alone. As a result, some manufacturers are investigating blended energy storage systems utilizing batteries plus ultracapacitors, which can augment the battery capabilities by providing an energy buffer. When combined with a battery, an ultracapacitor can remove the instantaneous peak energy demands that would normally be placed on the battery, as shown in the figure below. This can lengthen the battery's useful life and slow down the battery's loss of charging capacity over time.

- **Lithium pack with ultracapacitor combination**

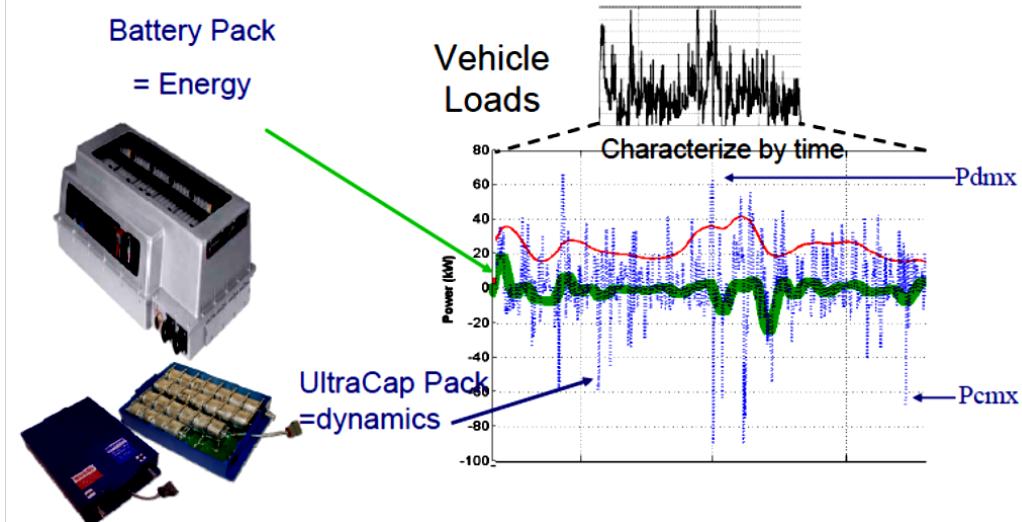


Figure 13: Pairing Ultracapacitor with Lithium Battery to Handle Vehicle Power Peaks

Source: Potential Ultracapacitor Roles for Hybrid Electric Vehicles Supercapacitor Seminar, 12/10/03
 Matthew Zolot, Tony Markel, Keith Wipke, and Ahmad Pesaran, National Renewable Energy Laboratory

²² Maxwell Technologies website. Retrieved November 21, 2011 from <http://www.maxwell.com/products/ultracapacitors/docs/MAXWELL TECHNOLOGIES PRODUCT COMPARISON MATRIX.PDF>

Ultracapacitors have physical capabilities that can overcome some of the limitations of lithium-based batteries as shown in the table below.

Table 6: Challenges for Lithium Batteries That Ultracapacitors Benefit

Ultracapacitor	Battery
Electrostatic, non-Faradiac	Electrochemical, Faradaic device
-40°C to +65°C	-20°C to +40°C
High efficiency: 98% to 92%	Moderate eff: 95% to 85%
High power: C-rates >1000	C<100 (at best)
Energy mgmt: cell over voltage	Energy mgmt: Cell equalization
Abuse and rapid discharge tolerant	Sensitive to rapid chg/dchg
Very wide SOC window	Lithium δ SOC<50%
Ease of SOC and SOH monitoring	Difficult algorithm for SOC, SOH

Source: Miller, Dr. John M., Maxwell Technologies. Energy Storage Technology, Markets and Applications, Ultracapacitors in Combination with Lithium-ion.

Lithium batteries have State-of-Charge (SOC) limitations based on both temperature and chemistry that impact charge/discharge rate limits. In comparison, an ultracapacitor maintains constant charge and discharge rates from 0 – 100% SOC. A lithium-based battery in an electrified vehicle application has a maximum theoretical SOC window of 70%. In practice, most manufacturers tend to operate batteries within a 50% SOC range, as shown in the figure below.

- Temperature and rate limits above 80% SOC
- Temperature and rate limits below 30% SOC
- PHEV's and battery-EV require >70% SOC window

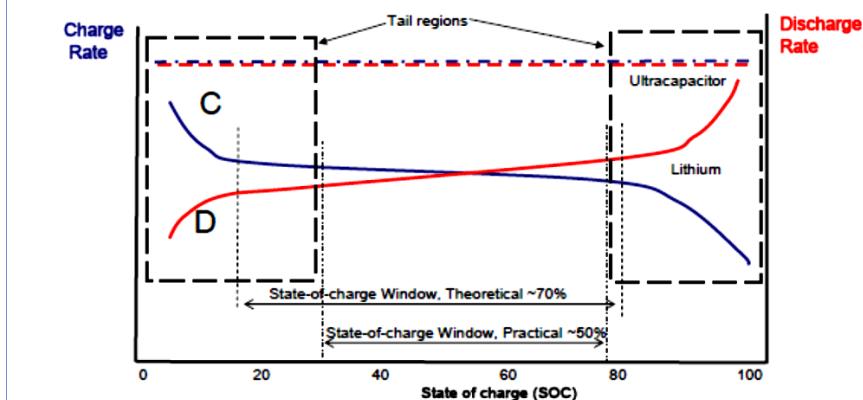


Figure 14: Lithium Battery State of Charge Limitations

Source: Miller, Dr. John M., Maxwell Technologies. Energy Storage Technology, Markets and Applications, Ultracapacitors in Combination with Lithium-ion.

Ultracapacitors can be used in conjunction with batteries to extend the usable SOC window, as well as allow higher peak charge and discharge rates. This is illustrated in the figure below which shows the theoretical improvement in usable SOC range on a Chevrolet Volt through the addition of ultracapacitors.

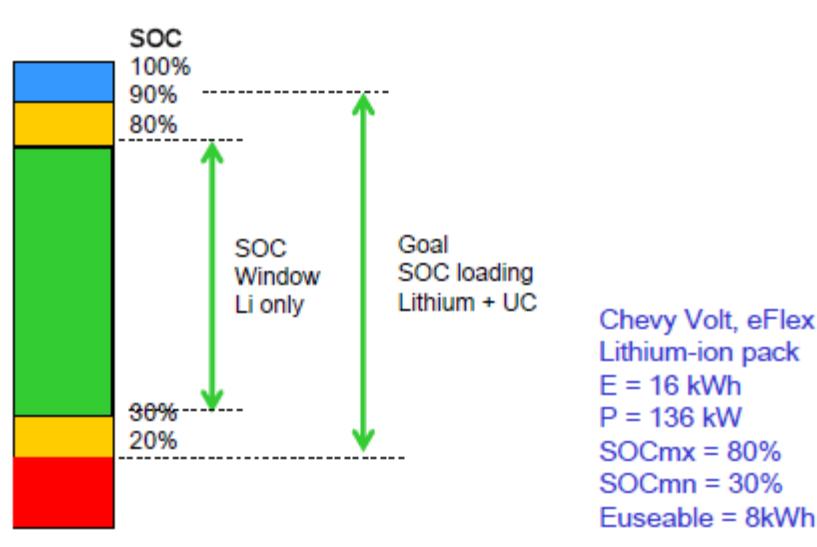


Figure 15: State of Charge Improvement by Pairing Ultracapacitor with Lithium Battery

Source: Miller, Dr. John M., Maxwell Technologies. Energy Storage Technology, Markets and Applications, Ultracapacitors in Combination with Lithium-ion.

One difficulty in quantifying the peak power and energy requirements for hybrid-electric vehicles is that the useable power and energy requirements can be highly dependent on the control strategy linking operation of the engine and electric drive system. In the case of a charge sustaining hybrid, the useable energy required can vary from 100-300Wh depending on how often and at what power level the engine is used to recharge the energy storage unit.^{23,24} In the case of plug-in hybrids, the peak power requirement depends on the blending strategy of the electric motor and engine when the vehicle is operating in the “all-electric” or charge depleting mode. If ultracapacitors and batteries are used together in either plug-in hybrid or electric vehicles, the strategy utilized for the load sharing between the two energy storage units has a large effect on the power requirements for each of them.

²³ Burke, Andrew. (June 1, 2007). Comparisons of Lithium-ion Batteries and Ultracapacitors in Hybrid electric Vehicle Applications. EET-2007 European Ele-Drive Conference, Brussels, Belgium.

²⁴ Peasaran A. (July, 2007). Factors and Conditions for Widespread Use of Ultracapacitors in Automotive Applications. Proceedings of the Advanced Capacitor World Summit 2007. San Diego, California.

Energy storage system considerations indicate that combinations of ultracapacitors and advanced batteries (>200 Wh/kg) are likely to prove advantageous in the future as such batteries are developed. This is particularly likely to be the case in plug-in hybrids with high power electric motors for which it may be difficult to limit the size and weight of the energy storage unit even using advanced batteries.²⁵

The most common design when pairing an ultracapacitor array with a battery is an active parallel configuration, where a power electronics converter manages and blends the power from both the battery and the ultracapacitor. One such configuration is illustrated in the figure below.

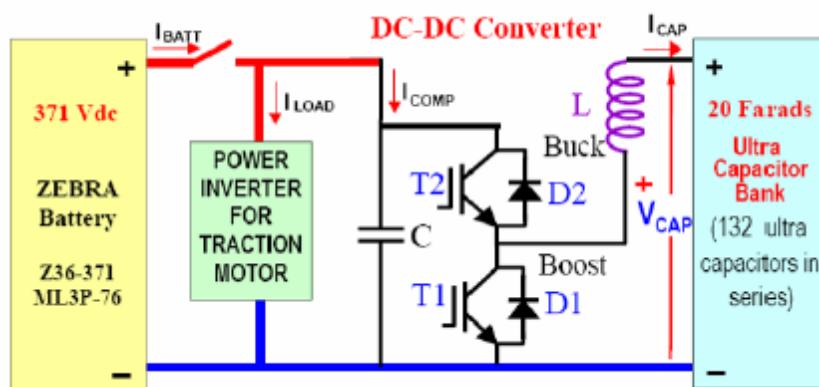


Figure 16: Active Parallel Configuration for Battery and Ultracapacitor

Source: Prof. Juan Dixon EVS22 paper, Yokohama, Japan, Oct. 22-28 2006. Originally developed and published by R. King, GE Global Research

3.3.5 Additional Requirements Such as On-board or Exportable Power

A key potential benefit of hybridizing a truck powertrain is the ability to generate power to satisfy other needs on-board the vehicle or at a work site. Many trucks are presently fitted with a generator or hydraulic pump to provide power for on-board equipment such as lifts and booms or refrigeration units. These are typically connected through a power take-off on the transmission or in the drivetrain. Other trucks such as over-the-road tractors need power for the electrical loads of a sleeper cab when the truck is parked. This can require the engine to be idled for extended periods to supply this

²⁵ Burke, Andrew. (April 14, 2009). Ultracapacitor Technologies and Application in Hybrid and Electric Vehicles.

power, using fuel and shortening maintenance intervals. Sometimes a separate auxiliary power unit (APU) is fitted to handle these electrical loads, allowing the primary engine to be turned off.

A hybrid-electric powertrain with an appropriately sized battery pack has the potential to replace these various methods for generating on-board power. If hardware such as a separate generator or APU can be replaced, this can reduce the incremental cost for hybridization. It can also lead to additional fuel savings if long engine idle periods can be eliminated. The greatest savings can accrue if a plug-in hybrid configuration is used where the battery has sufficient power to get through the on-board power demands of a typical work day without having to start the engine, and can then be recharged by plugging in to an off-board power source at night. Users of hybridized utility and telecomm trucks that operate equipment at a worksite have seen up to 60 percent total fuel savings compared to around 30 percent for similar size hybrid trucks being used in package delivery service.

Several manufacturers including Eaton and Odyne offer truck hybrid systems designed to provide on-board and exportable power. Odyne has a plug-in hybrid system that can power the hydraulic pump that moves the boom on a utility truck and also provide 110/220V job-site power and heat or cool the vehicle when the engine is off (see additional detail in Section 4.2). This capability is now showing up in light-duty trucks as well. Via Motors is offering converted Chevrolet 1500 pickup trucks and vans with extended range electric (EREV) powertrains that can provide up to 15 kW of 110 or 220 Volt export power. This could be used to power a house during a blackout or at a job site. These vehicles are PHEVs that can run up to 40 miles on battery power before the engine comes on to extend range to 300 miles total.²⁶

²⁶ Via Motors website. Retrieved January 17, 2012 from <http://www.viamotors.com/wp-content/uploads/VIA-VTRUX-Truck-Flyer-02.pdf>

4.0 Hybrid Truck and Bus Production – Present and Planned

Synopsis

A large number of new hybrid MD and HD truck and bus models have been introduced to the North American market in the last five years. These span the full range of MD and HD commercial vehicle classes, and also come in a wide variety of body configurations, as illustrated in the figure below.

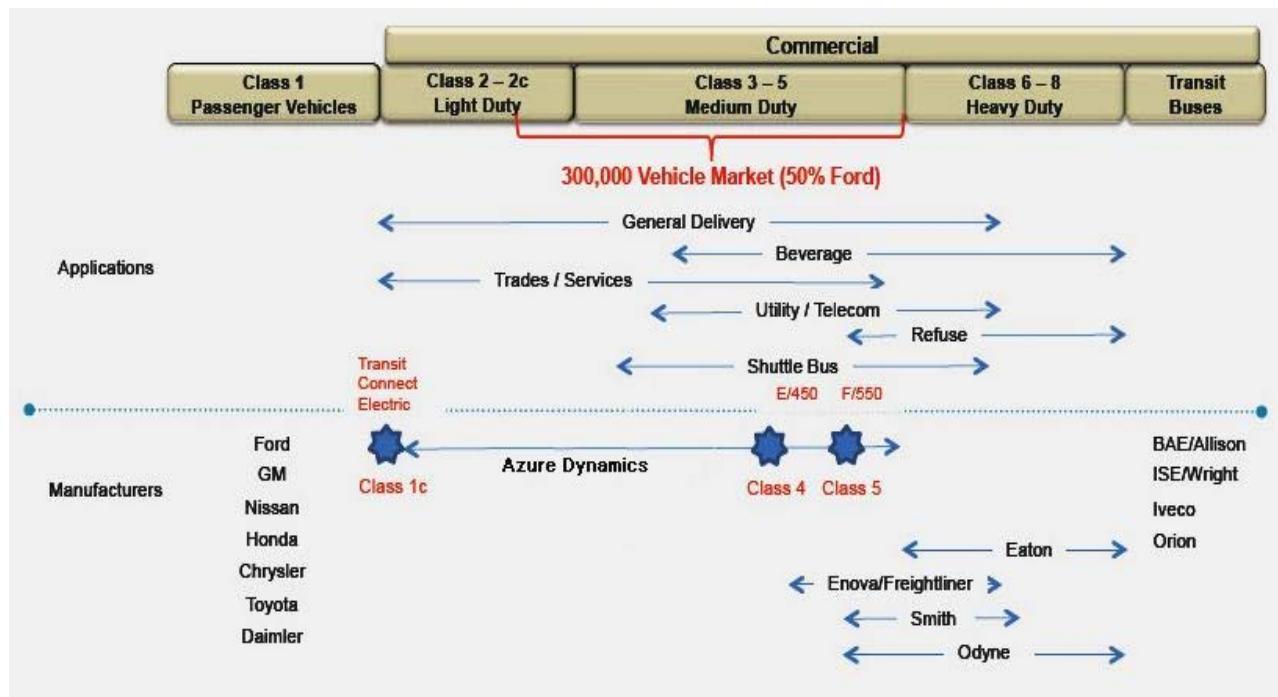


Figure 17: Hybrid Vehicle Availability in Commercial Segments

Source: Iacobelli, Ron. (October, 2011). Azure Dynamics OEM Presentation, HTUF 2011 National Conference.

Most of the major U.S. truck and bus manufacturers now offer at least one model with a diesel hybrid-electric powertrain, and some have several spanning multiple classes and chassis configurations. Other smaller manufacturers have focused on specific truck types such as utility boom trucks to develop specialized hybrid powertrains that are better able to meet unique requirements.

4.1 Hybrid Truck and Bus Original Equipment Manufacturers (OEMs)

Hybrid truck models are presently available from most U.S. truck makers, including major producers Daimler Trucks North America, Freightliner, International, Kenworth, and Peterbilt, plus smaller ones such as Odyne. The parallel hybrid-electric drivetrain system used in the majority of these trucks is manufactured by Eaton Corporation. The first U.S. truck maker to begin assembly line production of diesel electric hybrids was Navistar's IC Bus and Engine Corporation in October, 2007.²⁷

Diesel hybrid transit buses are currently being manufactured by around a dozen bus companies including Daimler's Orion Industries and Thomas Built divisions, Ebus Incorporated, New Flyer, Gillig, North American Bus Industries, and Nova Bus. Most of these use series hybrid-electric drivetrains, and key manufacturers are BAE Systems (HybriDrive), ISE Corporation (ThunderVolt), and GM's Allison Transmission. A majority of the hybrid buses in service are 40-foot buses. However, 22-foot shuttle buses and 60-foot articulated buses have also been deployed. There are also plug-in hybrid (PHEV) bus models on the market including two commercial bus models from Navistar's IC Bus group and a 22 ft. PHEV bus from Ebus Inc.

Several of these truck and bus manufacturers were interviewed during the research phase of this study to gain information on their present technology and future plans.

²⁷ Center on Globalization, Governance & Competitiveness, Duke Univ. (June 10, 2009). Manufacturing Climate Solutions -- Carbon-Reducing Technologies and U.S. Jobs.

4.1.1 Daimler Trucks North America

Daimler Trucks North America produces and sells a variety of hybrid trucks, school buses, and transit buses through its four divisions, Freightliner Trucks, Freightliner Custom Chassis Corp., Orion, and Thomas Built. Daimler is presently utilizing the Eaton parallel hybrid drive system in their trucks and school buses, and the BAE Systems series hybrid system in their Orion transit buses. Daimler has sold over 3,200 Orion Hybrid buses in North America and more than 1,500 Freightliner hybrid trucks.²⁸

Each of the Daimler parallel hybrid applications with the Eaton hybrid system has the following features and specifications:

- Engine - Cummins 6.7L ISB six-cylinder in-line diesel engine with a variety of horsepower/torque ratings up to 325 hp/750 ft lb torque.
- Transmission - Eaton Fuller automated-shift manual transmission
- Electric Drive - Traction motor/generator rated at 44kW output
- Battery Pack - Lithium-ion batteries, capacity 1.9kW-h
- Capable of electric launch and operation on the diesel engine or electric motor alone or in tandem

The Senior Manager for Hybrid Engineering at Daimler's Freightliner group provided the following information on Daimler's hybrid truck and bus models and future plans.²⁹

- The present Freightliner retail price premium for a Class 6-7 diesel-electric hybrid truck with the Eaton system is \$65,000, although market transaction prices can be 20 – 40% less than this, depending on volume. This can result in a payback of 9 – 10 years, depending on fuel and maintenance savings.
- Daimler is working on a new, in-house hybrid system design for future product applications that will feature a more powerful motor and larger battery pack. They see that larger utility truck customers are interested in more electric-only operation and engine-off running power, and the 44 kW motor in the Eaton system is not the most efficient for this.
- Daimler's goal for their new hybrid system is to achieve customer paybacks in 3 – 4 years through both lower cost and additional fuel savings.
- Daimler does not see customer demand for plug-in hybrid trucks since they need a very large battery pack to achieve gross vehicle weight requirements, and Daimler is not doing work on PHEVs. They presently sell an HEV bucket truck that

²⁸ Daimler website. Retrieved from <http://www.daimler.com/technology-and-innovation/drive-technologies/hybrid-drives>

²⁹ Interview. (September 8, 2011). Scott Larson, Senior Manager for Hybrid Engineering, Freightliner.

can run 10 – 15 minutes in electric-only mode with the engine off before restarting the engine to recharge the battery.

- Daimler does not see serious interest in blended ultracapacitor/battery arrays for hybrid trucks at this time.
- Daimler very much wants to be in the hybrid truck and bus business and is working to develop cost-effective technology. Daimler hopes to sell 3,000 – 5,000 hybrid trucks and buses per year in the near future when they begin producing their own hybrid system.

Freightliner Trucks – Produces the Freightliner Business Class M2 106 Hybrid, available in a wide variety of body and chassis configurations such as city delivery, utility, and urban tractor.

- Powered by a Cummins ISB 6.7 liter diesel engine with a variety of horsepower/torque ratings up to 325 hp/750 ft lb torque.
- Eaton hybrid system features an Eaton Fuller 6-speed Ultrashift transmission and an electric motor that provides up to an additional 60 hp and 310 ft lb torque.
- Operates using the diesel engine alone or in combination with the hybrid-electric motor. The hybrid motor provides additional power to launch the vehicle and improves fuel economy in stop-and-go operations.
- The system recovers the energy normally lost during braking and stores that energy in its lithium ion batteries.
- In 2011, Freightliner introduced an engine-off-at-stop feature that provides up to 8% additional fuel savings. When the service brake is applied, at a stop light for example, the engine turns off. When the service brake is released, the engine restarts.

The principal hybrid system components are packaged as indicated in the figure below.



Figure 18: Freightliner Business Class M2 106 Hybrid Component Packaging

Source: Freightliner website. Retrieved January 16, 2012 from
<http://www.freightlinertrucks.com/Trucks/Alternative-Power-Trucks/Hybrid-Electric>

The M2 106 Hybrid also features an optional 5 kW auxiliary power generation (APG) unit for additional fuel savings. The APG unit provides AC power for lights, tools or refrigeration units using only the power stored in the lithium ion batteries. This stored energy can also power electric-only operation for electric Power Take-Off (ePTO) use, such as running a utility lift. Using ePTO significantly reduces idle time and provides fuel savings of up to 60%.

The Freightliner M2 106 Business Class Hybrid truck comes in the following configurations and projected fuel savings.

Table 7: Freightliner M2 106 Business Class Hybrid Configurations

	City Delivery Hybrid	Utility Hybrid	Hybrid Delivery Tractor
GVW/GCW	up to 33,000 lb. GVW	up to 40,000 lb. GCW	up to 55,000 lb. GCW
PTO	Mechanical PTO Capability	Electronic PTO (ePTO) Capability	Mechanical PTO Capability
Fuel Savings	25-40%	40-60%	20-30%

Source: Automotive Insight, based on Freightliner website information

Freightliner has also developed a Hybrid Performance gauge to help drivers maximize the fuel economy of their hybrid trucks. Freightliner notes that driver technique can impact fuel efficiency by 10 – 20%.³⁰ This gauge shows the battery state of charge and the transmission gear. A needle indicates when mechanical brakes are being used rather than regeneration to slow the vehicle, and when excessive electrical assist is being used under acceleration.



³⁰ HTUF 2011 Show Times. (October 10 – 13, 2011). Freightliner Starts Start-Stop Truck Deliveries

Freightliner Custom Chassis Corporation (FCCC) - Produces Hybrid-Electric walk-in vans that utilize the Eaton diesel-electric parallel hybrid system. These hybrid vans come in two configurations – MT-45 covering Class 4 – 5 and MT-55 covering Class 6. The MT-55 truck is available with an engine idle-off feature and air brakes, providing an additional fuel economy improvement of 8 - 9 percent.

Claimed features and benefits by FCCC include:

- Over 40% improvement in fuel economy with no compromise in payload capacity
- Employs a sophisticated energy-management system that selects the most efficient mode of operation—diesel, electric or both
- Constantly recharges the batteries through regenerative braking
- Engine idle-off feature (MT-55) shuts engine down when vehicle stops, eliminating fuel consumption and emissions until throttle is engaged to restart the engine

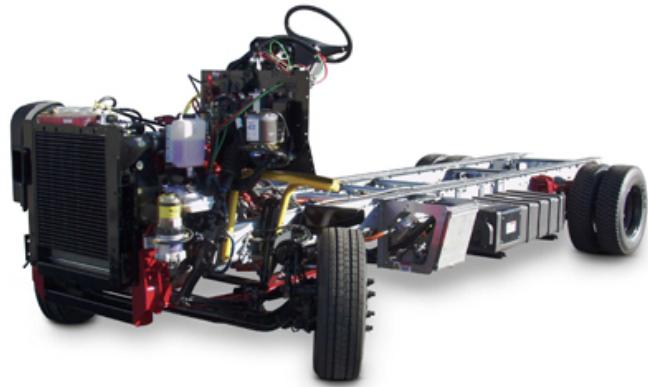


Figure 19: Hybrid-Electric walk-in van chassis from Freightliner Custom Chassis Corporation (FCCC)

Source: Freightliner website. Retrieved Jan. 5, 2012 from <http://freightlinerchassis.com/Walk-In-Van-Chassis/hev-chassis/menu-id-123.html>

Orion International – Produces the Orion VII low floor diesel-electric hybrid bus. Orion first teamed up with BAE Systems in 1996 to develop a series hybrid electric bus with a diesel engine. The resulting vehicle entered the market in 1998, and over 1300 had been placed in service by 2008 with another 1500+ on order. Orion is the largest diesel hybrid transit bus producer with approximately 60% market share. The largest fleet users are New York City, Toronto, and San Francisco.

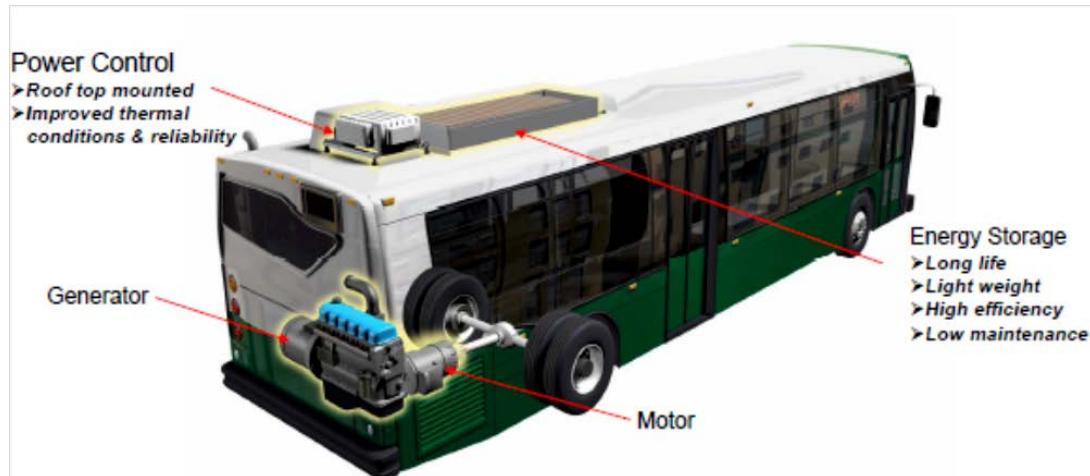


Figure 20: Daimler Orion VII Diesel Hybrid Electric Bus

Source: Orion International website. Retrieved from

http://www.dcbusna.com/Projects/c2c/channel/documents/845706_Orion_Hybrid_Transit_Presentation_Q1_2009.pdf

The Orion VII series hybrid transit bus has the following specifications:

- Engine – Cummins 5.9L ISB 260 HP six-cylinder Clean Diesel engine
- Generator – 160 kW
- Traction Motor – BAE AC Induction
- GVW Rating – 42,540 lb
- Length – 40 ft

The initial battery design in the Orion series hybrid bus was lead acid, however, Orion introduced Lithium-ion batteries beginning in 2007. Customer benefits according to Orion include:

- Less weight -- over 3,000 lbs less than previous design
 - Improved carrying capacity and fuel economy
- 6 year design life – twice as long as the previous design
 - Backed by 2 year standard or 5 year extended warranty
- Reduced maintenance -- no conditioning required, thus no additional depot equipment needed

The lithium-ion battery pack is assembled by BAE Systems with cells from A123. It is comprised of a single air cooled enclosure measuring 84 x 41 x 10 inches containing 16 individual modules, each weighing 18 lbs. One of these modules is shown in the figure at left below, while the overall battery pack is shown on the right.



Figure 21: Lithium-ion Battery Module and Pack as Used in Orion Hybrid Bus

Source: Orion International website. Retrieved from
http://www.dcbusna.com/Projects/c2c/channel/documents/845706_Orion_Hybrid_Transit_Presentation_Q1_2009.pdf

Fuel economy for the Orion VII hybrid transit bus is improved by 35 – 40% vs. a conventional diesel engine bus, resulting in a lifetime fuel savings of approximately 30,000 gallons, as shown in the figure below.

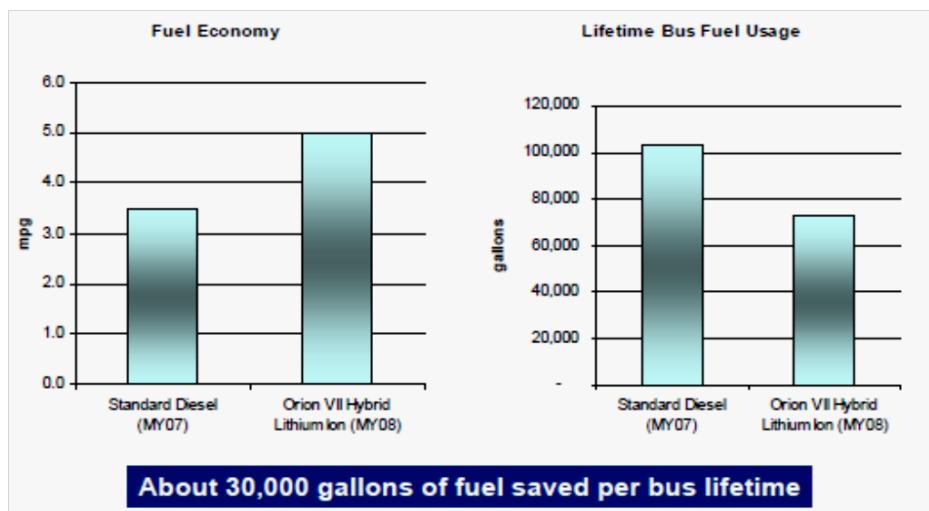


Figure 22: Fuel Economy and Lifetime Fuel Savings for Orion Hybrid Bus

Source: Orion International website. Retrieved from
http://www.dcbusna.com/Projects/c2c/channel/documents/845706_Orion_Hybrid_Transit_Presentation_Q1_2009.pdf

Daimler notes that the 5.9L I-6 diesel engine used in the Orion VII Hybrid bus is about half the size of the engine in a normal 40 ft. transit bus, which contributes to the fuel economy improvement. Claimed benefits include:

- Lower emissions (NOx, CO2)
- Increased fuel economy
- Improved reliability
- Utilizes existing diesel infrastructure
- Compatible with future power plant technologies such as ultra-clean fuel cells
- Proven in more than 10 million miles of service in New York City

Thomas Built Buses – Introduced the Saf-T-Liner® C2e Hybrid school bus in 2007 utilizing the Eaton parallel hybrid system. Specifications are as follows:

- Diesel Engine – Cummins 6.7L ISB six-cylinder in-line engine
 - Output of 200 HP rating with 520 ft-lb torque at 1600 RPM
 - Emissions meet EPA '10 standard
 - Optional B20 compatibility
- Transmission – Eaton automated manual transmission
- Drive System – Eaton parallel hybrid drive system/diesel-electric
 - Electric motor: output 44kW
 - Generator output: 44kW
- Battery Pack – Lithium-ion batteries, capacity 1.9kW/h
- Seating Capacity – Up to 81
- GVWR – 33,000 lbs.



Figure 23: Thomas Built Saf-T-Liner C2e Hybrid School Bus

Source: Thomas Built website <http://www.thomasbus.com/bus-models/green-buses/saf-t-liner-c2.asp>

4.1.2 Ebus Incorporated

Ebus produces the EBUS22HB plug-in, series hybrid-electric 22 ft. bus that offers greater range than battery-electric buses can provide. Designed to seat 22 passengers plus standees, this Ebus model is typically used in circulator, shuttle, campus and neighborhood service applications. This hybrid bus is propelled by electric motors powered by two nickel-cadmium (NiCd) traction battery packs. These are kept within a 60 – 80% state of charge (SOC) range by an on-board generator. Regenerative braking recovers energy during deceleration.

The series hybrid system uses a 30 kW Capstone MicroTurbine auxiliary power unit (APU) driving a generator as a primary powerplant. The APU can operate on diesel fuel or liquefied petroleum gas (LPG). This hybrid bus can be plugged into a charging system overnight to bring the batteries up to a 100% SOC for the morning pullout. It initially operates on battery power alone as a charge-depleting hybrid until SOC reduction activates the APU to generate power, allowing the bus to continue running in charge-sustaining mode.

The EBUS22HB Hybrid-Electric bus specifications are as follows:

- Power Generator: Capstone Model 330 Microturbine – 30kW nominal
- Drive Motor: Reliance AC Induction, air-cooled
- Battery System: Single string of 50 100AH, Nickel-Cadmium, Liquid-cooled, “fast charge” batteries — manufactured by Saft
- Battery Charger: 25KW overnight charger and/or 90KW Fast-Charger
- System Voltage: 300 volts
- Maximum Forward Speed: 45 mph
- Gradeability: Up to 18 Percent
- Range: 150 to 250 miles
- Energy efficiency: 0.7 -1.4 kWh/Mile (gross DC)
- Price: \$325,000

The system diagram for this Ebus hybrid powertrain is shown in the figure below.

EBUS - HYBRID BUS PROPULSION SYSTEM

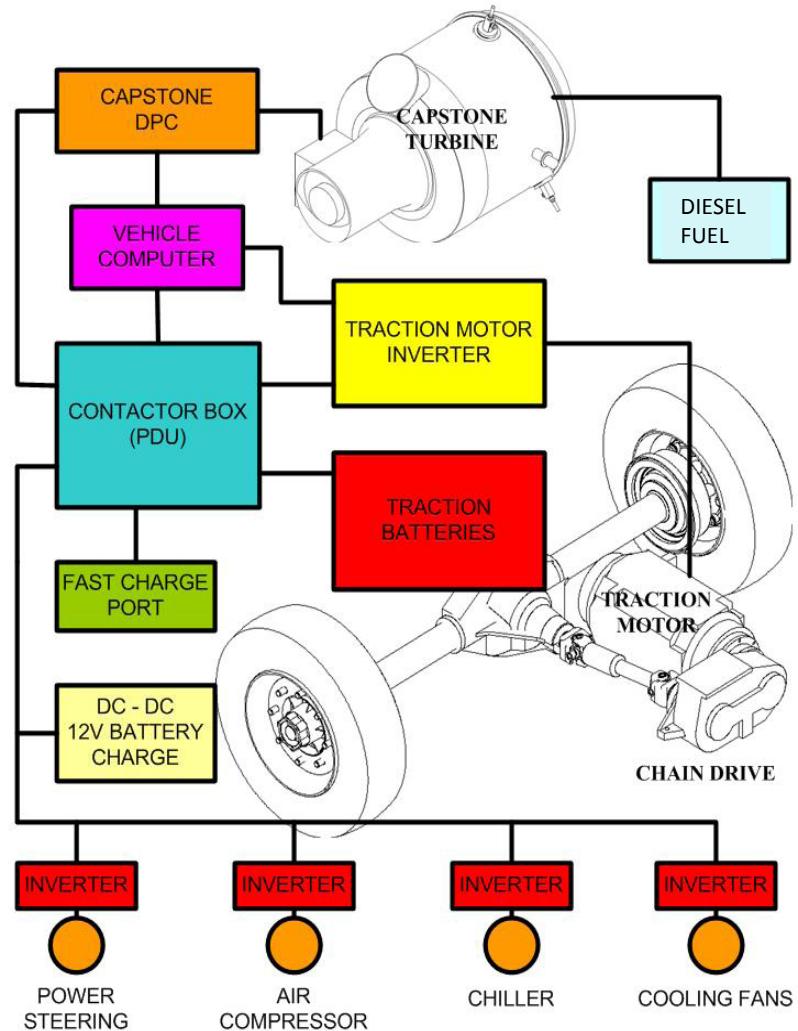


Figure 24: Ebus Hybrid Bus System Block Diagram

Source: Ebus website.

4.1.3 Hino Trucks

Hino has recently announced a new line of Class 4 and 5 trucks for the U.S. market that are available with either diesel or diesel-electric hybrid powertrains. The 155h Class 4 and 195h Class 5 hybrid cab-over engine (COE) trucks both feature Hino's 5 liter J05E Series engine producing 210 HP and 440 lb.-ft. of torque, and an Aisin A465, 6-speed automatic transmission.



Figure 25: Hino Class 4 and 5 Hybrid Truck

Source: Hino Trucks website. Retrieved January 12, 2012 from http://www.hino.com/coe/story_922.php

Hino has produced a variety of diesel-electric hybrid trucks for the Japanese and other markets, and claims that these trucks benefit from six generations of technology evolution and more than 10,000 production vehicles already on the road. Hino is a division of Toyota, so also has the benefit of Toyota's extensive hybrid powertrain experience in light-duty vehicles.

The Diesel-Electric Hybrid System Power Control Unit contains a nickel metal hydride battery pack produced by Primearth EV Energy (formerly Panasonic EV) along with the hybrid controllers. It features a Hybrid Adaptive Control System that continuously communicates with the Engine Control Unit (ECU) to evaluate driving and road conditions to optimize the truck's fuel economy and performance.



Figure 26: Hino 155h/195h Hybrid Control System and ECO Drive Display

Source: Hino Trucks website. Retrieved January 12, 2012 from http://www.hino.com/coe/story_922.php

The Hino trucks also feature a Hybrid System Mode Indicator and ECO Drive Display that is designed to keep the driver informed of the Hybrid system's operating mode and provide visual feedback (display turns green with optimized ECO driving) to encourage fuel efficient driving and reduced emissions.

4.1.4 Kenworth Truck Company (PACCAR Inc.)

Kenworth began full production of medium duty, diesel-electric hybrid trucks using the Eaton parallel hybrid system in 2008. It now offers the hybrid powertrain option on its T270 Class 6 and T370 Class 7 truck models. Kenworth's goal is to enhance fuel economy by up to 30 percent in pickup and delivery applications and up to 50 percent in utility operations.



Figure 27: Kenworth T370 Class 7 Hybrid Truck

Source: Kenworth website. Retrieved December 15, 2011 from
<http://www.kenworth.com/environmental.asp#>

The Kenworth T270 and T370 hybrids feature the following equipment:

- PACCAR PX-6 6.7L engine rated from 200 - 300 hp and 520 - 620 lb-ft torque
- Eaton Fuller 6-speed UltraShift® transmission with integral transmission-mounted motor/generator
- Frame-mounted 340-volt, lithium-ion battery pack
- Dedicated power management system
- Optional electric Power Take-off (ePTO)

Advanced powertrain controls monitor driving conditions and automatically select the ideal power mode, smoothly switching among electric only, combined diesel and electric, and diesel only power modes. Above 30 mph, the Kenworth hybrid operates like a standard diesel vehicle with all power coming from the engine during steady driving conditions. Below 30 mph, it uses a combination of diesel and electricity with the system automatically switching between the two modes of operation.

The hybrid system is monitored through a dash mounted display. As the power requirements for different driving conditions change, the screen constantly updates with the state of the system and horsepower generated by the hybrid system, as shown in the figure below.



Figure 28: Kenworth Hybrid System Monitor Display

Source: Kenworth website. Retrieved December 15, 2011 from
<http://www.kenworth.com/flashpopup.asp?name=KWHybrids&w=680&h=480>

Kenworth (along with Peterbilt) is also doing development work with turbine manufacturer Capstone on turbine-electric series-hybrid Class 7 and 8 trucks. One concept truck was running and another being assembled as of October, 2011. Each truck uses a Capstone C65 microturbine, which produces 65 kilowatts (87 horsepower) and is emissions certified by the California Air Resources Board. The "ranged extended" trucks will quantify the performance, efficiency, and economic benefits of a microturbine-based series-hybrid system for large trucks. This type of powertrain is already being used in transit buses.³¹

³¹ TruckingInfo.com website. Retrieved January 24, 2012 from http://truckinginfo.com/news/news-detail.asp?news_id=75148&news_category_id=36

4.1.5 Mack Trucks Inc. (Volvo Group)

Mack Trucks does not yet have any diesel-electric hybrid truck models in series production, although its parent company Volvo has built diesel hybrid buses for the European market. Mack has built some demonstrator vehicles, and is working with both sanitation fleets and the U.S. Air Force to evaluate the potential fuel savings for hybrid sanitation trucks and refueling vehicles.

Mack delivered a diesel-electric version of its TerraPro Low Entry model refuse truck to the New York City Department of Sanitation in spring, 2009 for fleet evaluation. This was the first Class 8 Diesel-electric hybrid designed to meet the new EPA 2010 truck emission standard. The sanitation department is using the model in its day-to-day operations and collecting feedback from drivers – critical information that Mack will need to begin offering hybrids as a standard option for customers. It is pictured below.



Figure 29: Prototype Mack Class 8 Hybrid Refuse Truck

Source: Mack Trucks website. Retrieved January 13, 2012 from
<http://www.macktrucks.com/default.aspx?pageid=2207>.

Mack estimates that a refuse collection truck equipped with hybrid technology could save 10,000 gallons of fuel per year, compared to its conventionally powered counterpart. This truck would also contribute less noise to the residential environment as a result of the hybrid drive used for launching the vehicle.

Mack and the U.S. Air Force have jointly developed hybrid technology prototypes of an aircraft refueling vehicle. The refueling application requires the vehicle to start and stop dozens of times a day. The frequent braking charges the prototype hybrid drive, which then supplies the electricity to assist the diesel engine on launching the vehicle – making hybrid drive an ideal choice for the application. Mack has also developed hybrid dump trucks for the Air Force, as pictured below, and is continuing to work with the Air Force on refining hybrid electric drive technology.



Figure 30: Mack Hybrid Dump Truck Demonstrator Developed for U.S. Air Force

Source: Mack Trucks website. Retrieved January 13, 2012 from
<http://www.macktrucks.com/default.aspx?pageid=2207>.

4.1.6 Navistar

In 2007, Navistar's International Truck and Engine Corporation became the first company to enter hybrid commercial truck production with the International DuraStar Hybrid diesel-electric truck. International teamed with the Hybrid Truck Users Forum (HTUF), Eaton Corporation and the US Government to develop 24 prototype hybrid utility trucks that were put into fleet service in 2006 with 14 utility companies such as Florida Power & Light. The success of these vehicles and customer feedback received led Navistar to introduce their first commercial hybrid truck in 2007.³²

International Truck and Engine Corp. – Produces the DuraStar 4300 Hybrid medium-duty truck in a variety of body configurations. This truck utilizes the Eaton parallel hybrid drive system. Specifications are as follows:

- Engines – International MaxxForce DT 7.6L in-line six-cylinder
 - 215 HP @ 560 lb-ft to 260 HP @ 660 lb-ft
- Transmission – Eaton Fuller Hybrid Drive 6-speed Automated Manual
- Optional electric Power Take-off (ePTO)
- Hybrid Storage Battery – 340 Volt Lithium Ion (Nominal)
- GVW – 23,500 – 44,000 lbs.
 - Rear Axle 12,200 - 23,000 lb. Capacity
 - Front Axle 8,000 - 14,000 lb. Capacity
- Wheelbase 152" to 254"
- Cab – Day, Extended, or Crew Cab

³² Navistar Press Release. (November 8, 2007). International Truck and Engine First Company to Enter Hybrid Commercial Truck Production. Retrieved from <http://ir.navistar.com/releasedetail.cfm?releaseid=274937>



Figure 31: Navistar DuraStar Hybrid 4300 Bucket Truck

Source: Navistar

Navistar claims that the DuraStar Hybrid provides dramatic fuel savings—from 30% to 40% on standard in-city pickup and delivery applications and more than 60% in utility-type applications. Under heavy acceleration or when climbing a hill, the electric motor can add up to 60 hp and 310 lb.-ft. of torque to the base MaxxForce engine rating. In addition, the optional Electric Power Take-Off (EPTO) can keep the engine off during stationary work for reduced noise.

IC Bus – Navistar’s IC Bus division offers two different bus model lines with diesel-electric hybrid powertrains, the CE Series and the HC Series.

The **CE Series** bus is available with a choice of two hybrid systems – charge sustaining or charge depleting (plug-in). Both utilize a post-transmission design with parallel system architecture to allow the bus to remain fully drivable with the hybrid system on or off. Both versions are available with the customary MaxxForce 7 diesel engine ranging from 220hp/560 lb-ft to 260hp/660 lb-ft, plus an Allison 2500 transmission.

Details for the charge depleting PHEV configuration include:

- Enova Systems induction motor rated at 80 kW peak/25 kW continuous
- Two Li-ion, liquid-cooled battery packs
- Software calibrated to balance battery management and diesel engine power

- Charge depleting range of 40 miles with up to 65% fuel economy improvement and 39% reduction in greenhouse gases running from 100% to 25% battery SOC
- Adds about 2,000 lbs and \$100k to bus price



Figure 32: IC Bus CE-Series Hybrid School Bus

Source: IC Bus website. Retrieved from
<http://www.icbus.com/ICBus/buses/schoolroute/ceserieshybrid/overview>

The **HC Series** hybrid bus from IC Bus utilizes the standard Eaton parallel hybrid system with a 44 kW motor/generator combined with a six-speed auto-shift manual transmission, and 1.9 kWh Li-ion battery pack. IC Bus claims up to a 32% improvement in fuel economy over the standard diesel-engine configuration.



Figure 33: IC Bus HC Series Hybrid Bus

Source: IC Bus Website. Retrieved January 19, 2012 from
<http://www.icbus.com/ICBus/buses/commercial/hcserieshybrid/overview>

4.1.7 Nova Bus (Volvo Group)

Nova Bus produces their LFS model diesel-electric hybrid bus that utilizes the GM Allison Transmission hybrid drivetrain. The bus is powered by a Cummins 6.7L ISB 280 hp diesel engine connected to an Allison H40 EP transmission that acts as both a generator and electric motor. The battery pack, weighing approximately 900 lbs, is on the roof of the bus. As the vehicle accelerates from a stop, the electric drive predominates. Mechanical drive gradually blends with electric drive until the vehicle attains highway speeds; the drive then becomes purely mechanical. The system configuration is pictured below.

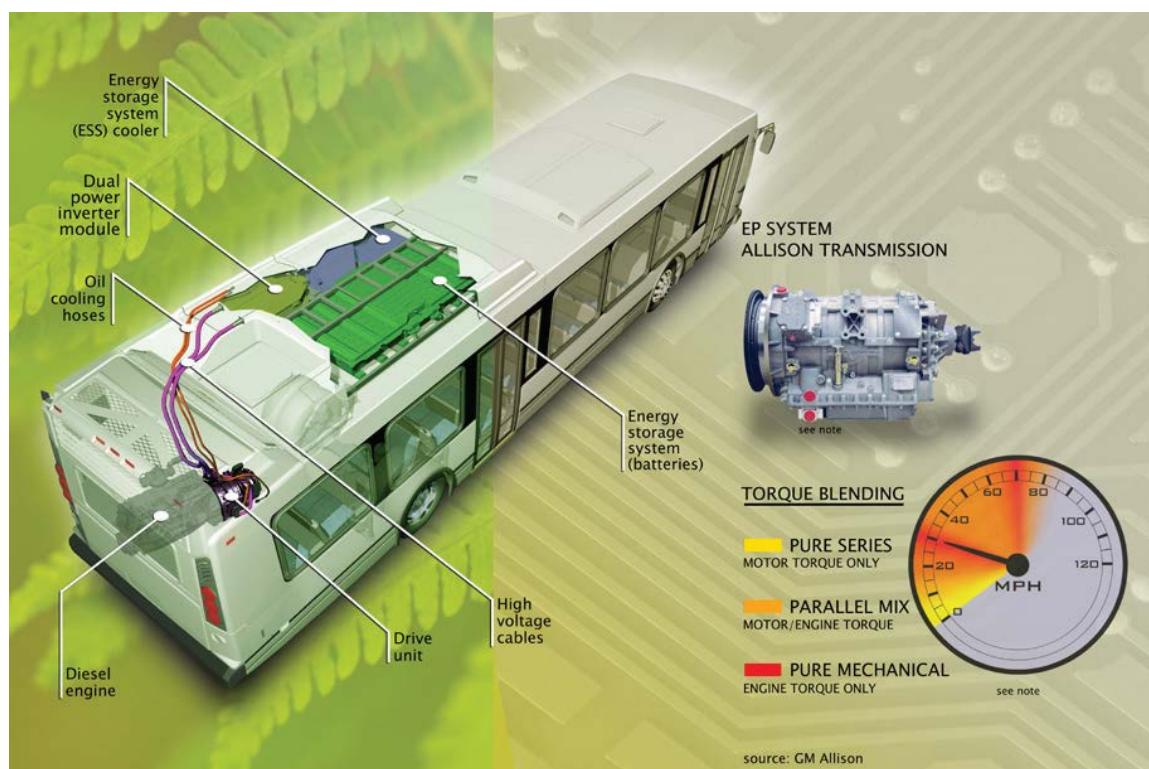


Figure 34: Nova Bus LFS Hybrid Bus Configuration

Source: Nova Bus website. Retrieved January 12, 2012 from
http://www.novabus.com/documents/fiche_hybrid_english_FINAL.pdf

Nova Bus lists the following benefits of operating a Nova LFS HEV:

- Offers up to 40% reduction in fuel consumption while utilizing existing infrastructure.
- Provides savings on engine and brake maintenance costs since hybrid configuration puts less stress on them.
- Maximizes energy efficiency: 280 HP engine optimizes vehicle weight.
- Maintains and enhances air quality and reduces greenhouse gas emissions by up to 40%.
- Provides a quiet and smooth ride.

Nova Bus LFS HEV Technical Specifications

- Seating Capacity: Up to 41
- Electric / Electronic system: Volvo Bus Electronic Architecture (V-BEA)
- Outer shell: Fiberglass and thermoplastic skirt panels
- Length: 40 ft.
- Structure: Stainless Steel
- Engine: Cummins ISB 6.7 280 HP
- Electric Drive: Allison H 40 EP
- Battery Pack: Roof mounted, 900 lb weight
- Brakes: All-wheel disk brakes
- Fuel Tank Capacity: 82 US gal. or 125 US gal.

4.1.8 Peterbilt Motors Company (PACCAR Inc.)

Peterbilt offers a variety of diesel-electric hybrid truck models that utilize the Eaton Hybrid System and span truck Classes 6 - 8. These include the Model 330, 337, and 348 Hybrid trucks with a wide variety of wheelbases, chassis configurations, and body styles. Peterbilt notes that the included lithium-ion battery pack provides the highest energy density of any available battery technology. In fact, the battery used for this system weighs approximately 110 lbs and is equivalent to 1900 lbs of conventional lead acid batteries.

The Peterbilt 330 and 337 hybrids feature the following equipment:

- PACCAR PX-6 6.7L engine rated from 200 - 300 hp and 520 - 620 lb-ft torque
- Eaton Fuller 6-speed UltraShift® transmission with integral transmission-mounted motor/generator producing 44 kW (60 HP)
- Combined power of 320 HP and a torque-limited 860 lb-ft torque
- Frame-mounted 340-volt, lithium-ion battery pack
- Dedicated power management system
- Optional electric Power Take-off (ePTO)

Peterbilt has redesigned the battery box for 2011 to neatly package the majority of the unique hybrid components in addition to many of the standard items conventionally located in this area. This battery box contains the following: hybrid drive cooler, air tanks, conventional 12 volt batteries, 340 volt DC to AC inverter, and 12 volt converter. There is also a unique Hybrid System Monitor that displays the status of the hybrid system, power flows, and battery state-of-charge to the drive on a screen in the instrument panel. The packaging of the hybrid components plus the appearance of this system monitor are shown in the figure below.



Figure 35: Peterbilt Hybrid Component Packaging and System Monitor

Source: Peterbilt website. Retrieved January 19, 2012 from <http://www.peterbilt.com/eco/Design-Hybrid.htm>

Peterbilt's Model 330 Hybrid is their Class 6 hybrid vehicle offering, and is available with a 26,000-pound GVW rating. Peterbilt claims that it meets the needs of a wide variety of medium duty applications and is ideal for lease, rental and all van body applications. The Model 330 Hybrid can also be configured for non-commercial drivers' license (CDL) operation with hydraulic brakes for a greater range of driver options. At the heart of this Class 6 vehicle is a lightweight, all-aluminum cab and an ergonomic interior designed for comfort and productivity. The integration of the Eaton Hybrid Drive System and the 260-horsepower PACCAR PX-6 engine delivers up to 860 ft-lbs of torque. Launching the vehicle electrically in an urban driving cycle can easily achieve fuel economy benefits in excess of 30%.



Figure 36: Peterbilt Model 330 Class 6 Hybrid Truck Chassis

Source: Peterbilt website. Retrieved from <http://www.peterbilt.com/eco/ReadyTrucks-MediumDutyHybrids.htm>

Peterbilt's medium-duty Model 337 Hybrid is available in a Class 7 configuration for a wide array of applications including inter- and inner-city pickup and delivery, fire and rescue, beverage, municipal and refuse. The Model 337 Hybrid utilizes components that provide up to an 80% reduction in engine idling and a 30 to 40% improvement in fuel efficiency. Configured for a utility application, further savings are realized through on-road and electric operation of the Power Take-Off (PTO) using the on-board lithium-ion batteries, which allow the body to operate with the engine off. Once this power is depleted, an automatic engine start and shut down sequence occurs to recharge the batteries.



Figure 37: Peterbilt Model 337 Class 7 Hybrid Truck

Source: Peterbilt website. Retrieved from <http://www.peterbilt.com/eco/ReadyTrucks-MediumDutyHybrids.htm>

The Model 386 HE Class 8 Hybrid combines aerodynamic styling and the versatility of a detachable sleeper with fuel-efficient hybrid technology for on-highway and bottom line performance. When coupled with a more constant speed drive cycle, the Model 386 HE can increase fuel economy. While driving, the Model 386 HE system recovers energy normally lost during downhill coasting, deceleration, or braking and stores it in the system's batteries. The system's motor/generator uses this stored energy to provide torque to the truck's driveline to improve vehicle performance, operating the engine in a more fuel-efficient range or to operate only with electric power.

The hybrid system also improves fuel efficiency and lowers emissions by powering the heating, air conditioning and vehicle electrical systems while the engine is off. When the idle reduction mode on the Model 386 HE is active, engine operation is limited to battery charging, an automatically controlled process that takes approximately five minutes per hour to fully charge the system.



Figure 38: Peterbilt Model 386 HE Class 8 Hybrid Truck

Source: Peterbilt website. Retrieved from <http://www.peterbilt.com/eco/ReadyTrucks-HeavyDutyHybrids.htm>

Peterbilt is also participating with Cummins in the SuperTruck project sponsored by the U.S. Department of Energy (DOE), with \$39 million in funding having been awarded by the U.S. Secretary of Energy. The goal of the SuperTruck program is to improve long-haul Class 8 vehicle freight efficiency through advanced and highly efficient engine systems and vehicle technologies that also meet prevailing emissions and Class 8 tractor-trailer vehicle safety and regulatory requirements.³³

The SuperTruck project will develop and demonstrate a highly efficient and clean diesel engine, an advanced waste heat recovery system, and a fuel cell auxiliary power unit to reduce engine idling on an aerodynamic Peterbilt tractor and trailer combination. The SuperTruck will result in a fuel-efficient, low emissions diesel engine that achieves a significant fuel economy improvement over current diesel technology.

³³ Peterbilt website. Retrieved from <http://www.peterbilt.com/eco/navigator.htm>

4.1.9 VDL Bus and Coach

VDL is a European bus manufacturer that is notable for offering a series hybrid diesel-electric bus that uses ultracapacitors for energy storage and hub motors integrated into the rear axle to drive the wheels. VDL's Citea SLF-120/hybrid utilizes the diesel engine to drive a generator that produces the electrical power. This power is used to drive the hub motors installed in the rear axle, or is stored in ultracapacitors for later use. The braking energy is also recovered and stored in these ultracapacitors for reuse during driving. The diesel engine can shut off at bus stops and whenever the bus comes to a standstill.



Figure 39: VDL Citea SLF-120/hybrid Transit Bus

Source: VDL Bus and Coach website. Retrieved from
<http://www.vdlbuscoach.com/Producten/Openbaar-vervoer/Citea.aspx>

The Citea SLF-120/hybrid bus is available in 3 versions: the 'Basic Hybrid', the 'Basic Zero Emission Hybrid' and the 'Advanced Zero Emission Hybrid'. The latter version has sufficient energy storage capacity to use only the electric drive motors when accelerating from a stop. It is possible to drive a pre-established part of a route entirely on electric power, producing zero emissions as well as less noise.

The Citea SLF-120/hybrid bus has the following specifications:

- Cummins 4.5L ISB 4-cylinder diesel engine producing 207 hp (152 kW) and 560 lb-ft (760 Nm) torque
- Vossloh Kiepe series hybrid drive system with generator, power electronics and ultracapacitor energy storage
- ZF AVE 130 electric-drive axle with 2x120 kW (163 hp) water-cooled, asynchronous hub motors
- GVW – 41,887 lb (19,000 kg)

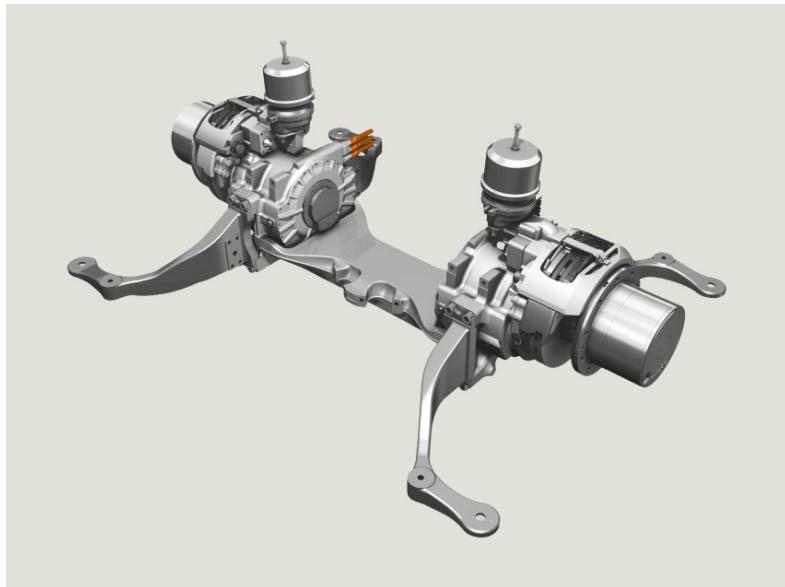


Figure 40: ZF AVE 130 Electric Drive Axle used in Citea SLF-120/hybrid Bus

Source: ZF website. Retrieved from

http://www.zf.com/corporate/en/press/media_service/images/product_images/product_images.jsp

4.2 Hybrid Propulsion System Manufacturers and Converters

There are a few powertrain manufacturers that produce the diesel-electric hybrid drivetrains that are used in most of the MD and HD hybrid trucks and buses manufactured by the OEMs. The heavy truck industry has traditionally used transmissions and axles from outside suppliers, and some of these companies such as Eaton Corp. and Allison Transmission took the initiative to develop hybrid drivetrains that could be sold to a number of users. Since individual truck model volumes can be very low, this helps to generate the hybrid system volumes needed to make the investment worthwhile.

There are also a number of companies that produce hybrid drivetrains and do the aftermarket conversions to hybridize medium duty trucks and shuttle buses. In some cases these are sold by the converter, and in others go back through the OEM truck maker's dealer network. These hybrid powertrain manufacturers and converters are detailed in this section.

4.2.1 ALTe Powertrain Technologies

ALTe Powertrain Technologies is developing a series Plug-in hybrid powertrain conversion kit for non-hybrid vehicles. Their initial focus is on fleet vehicles such as taxis, limos, delivery trucks, vans and shuttle buses in the light to medium duty classes.

- The series hybrid powertrain kit replaces the vehicle's conventional engine and transmission with a traction motor powered by a 20kWh lithium-ion battery pack, a 4-cylinder engine/generator set, a hybrid controller unit and other parts.
- Range is approximately 40 miles on the battery before the engine/gen set turns on to produce power to recharge the battery and/or feed the traction motor.
- The conversion cost is projected to range from \$26,500 to 32,000 per vehicle.
- ALTe claims increased fuel efficiency of up to 200% when compared to a base factory fleet vehicle with a V8 engine.
- The company is targeting vehicles from model years 2004 to 2010 for the retrofit, with a particular emphasis on vans and trucks from 2006 to 2008.
- ALTe has partnered with Manheim, the auto auction company, to retrofit this kit to existing vehicles. It hopes to deliver its powertrain kit to Manheim service locations in Atlanta, Los Angeles and New York City starting in spring, 2012.

The ALTe series hybrid rolling chassis is shown in the figure below. The Li-ion battery packs are the large green boxes in the center.



Figure 41: ALTe Series PHEV Rolling Chassis

Source: ALTe website. Retrieved Jan. 7, 2012 from http://altept.com/?page_id=428&album=2&photo=35

4.2.2 Azure Dynamics

Azure Dynamics Corporation (AZD) is a leader in the development and production of hybrid electric and electric components and powertrain systems for commercial vehicles. Azure is targeting the medium-duty delivery vehicle and shuttle bus markets and works closely with Ford Motor Company to convert Ford E-450 vehicle chassis with hybrid-electric powertrains. The vehicles then go on to body fitters, and Azure has recently negotiated with Ford to sell the completed vehicles through the Ford dealer system.

Azure HEVs

While not presently a diesel truck hybrid, the AZD Balance Hybrid Electric drive system is worth noting because it has a 60% share of the medium duty (Class 2c – 5) hybrid commercial truck market in North America. The basic design could also be adapted to a variety of diesel engine truck chassis.

Azure is applying the Balance hybrid system to Ford's E-450 Cutaway and Strip Chassis trucks. This system augments the Ford 5.4L V8 gasoline engine and 5-speed automatic transmission to improve fuel economy by up to 40%. The hybrid features electric launch assist, electric-only propulsion up to 20 mph, engine-off at idle, and regenerative braking. On January 12, 2012, Azure announced that it has delivered its 1000th Balance Hybrid Electric Truck to Purolator, Azure's largest customer (with 555 units).

This hybrid design uses a 100 kW AC traction motor mounted between the conventional transmission and the rear axle. This is powered by a 345V Li-ion battery pack produced by Johnson Controls Inc. An ISG motor/generator is added to the front accessory drive to quickly restart the engine under acceleration, recharge the battery pack, and also power the accessories through a clutched FEAD when the engine is off. The Azure system retains the stock GVWR of the Ford E-450 chassis, and is being used primarily in shuttle buses and delivery vans.

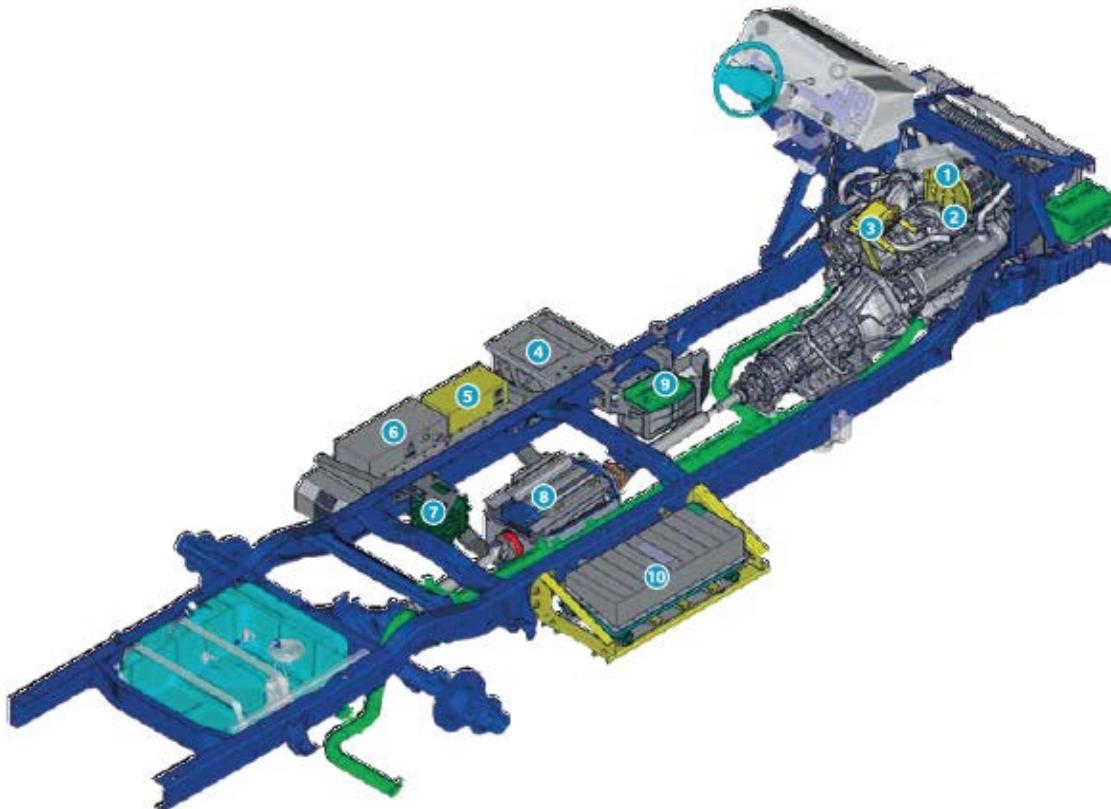
Specifications for the AZD hybrid drive system are shown in the table below.

Table 8: Azure Dynamics Balance Hybrid System Specifications

Manufacturer	Azure Dynamics
Model Year	2011, 2012
Model	Balance™ Hybrid Electric (Parallel Hybrid)
Motor	100 kW AC induction w/ regenerative braking
Motor Controller	120 kW Inverter
Transmission	Elect. 5-Spd Torqshift Auto O/D Transmission
Battery	345V, 6.8 Ah, maintenance free Li-Ion Automatic high voltage disconnect in case of vehicle collision
System Voltage	345V DC Nominal
Power Steering/Brakes	Engine on – standard engine driven pump Engine off – engine pump driven by ISG
Low Voltage System (12V)	Alternator supplemented by DC/DC converter
Cooling ¹	Engine – Ford cooling system with electrified radiator cooling fans Hybrid system – Separate low temperature cooling loop
Engine	Ford 5.4L EFI FFV Gasoline V8 Engine (50 State)

Source: Azure Dynamics Balance Hybrid Specifications & Ordering Guide - 2011/2012 Ford E-450 Cutaway & Stripped Chassis. Retrieved January 7, 2012 from
<http://www.azuredynamics.com/products/SPC500985-B.pdf.pdf>

The Azure Balance Hybrid architecture and key components are illustrated in the figure below.



* Balance™ Hybrid Electric Architecture diagram is representative, not actual.

1. INTEGRATED STARTER/GENERATOR (ISG) Used to start the engine and to generate power.	6. TRACTION MOTOR CONTROLLER Converts DC from the battery to 3 phase AC for the traction motor. Controls the speed and torque of the traction motor.
2. CLUTCHED FEAD Clutch at crank shaft opens when engine off & ISG then spins the disconnected Front Engine Accessory Drive (FEAD) system (power steering/brake pump, water pump, alternator & A/C compressor).	7. DC/DC CONVERTER Converts high-voltage DC power to keep the 12V batteries charged and to supply power for 12V accessories.
3. VEHICLE CONTROL UNIT (VCU) Controls all hybrid components and coordinates their operation with the Ford systems (e.g. start/stop).	8. TRACTION MOTOR Converts electrical energy to wheel torque in order to propel the vehicle. Speed & torque outputs are based on accelerator input as well as vehicle operating conditions.
4. HIGH VOLTAGE JUNCTION BOX Distributes DC power from battery to components and contains high voltage fuses.	9. 2ND 12 VOLT BATTERY An optional 2nd 12V battery is available, however not typically required.
5. ISG MOTOR CONTROLLER Converts DC from the battery to 3 phase AC for the ISG motor. Controls the speed and torque of the ISG motor.	10. ENERGY STORAGE SYSTEM (ESS) HIGH VOLTAGE BATTERY PACK Liquid cooled high voltage Li-Ion battery pack. Stores energy and includes internal sensors and controller.

Figure 42: Azure Dynamics Balance Hybrid Architecture

Source: Azure Dynamics Balance Hybrid Specifications and Ordering Guide. Retrieved Dec 5, 2011 from <http://www.azuredynamics.com/products/SPC500985-B.pdf.pdf>

Azure PHEVs

In October, 2011, Azure Dynamics announced a new medium-duty plug-in hybrid truck conversion based on their proven Balance HEV architecture. Automotive Insight interviewed the Chief Technology Officer for Azure Dynamics, and learned the following details regarding this program. This PHEV will be based on the Ford E-450 chassis with a GVW rating of 14,000 lb. It will use the same 14 kWh JCI battery pack that AZD uses in their EV conversion of the Ford Transit Connect (also used in the Odyne PHEV system). There will be a 50 kW primary traction motor and a separate integrated starter/generator (ISG) used to start the engine and provide power to the accessories. This PHEV will be capable of recharging the battery in just 3 – 4 hours on a 240V/30A power supply. It has the capability for all-electric drive at low vehicle speeds.³⁴

Azure Dynamics has also announced that they are working with Ford to develop a plug-in hybrid version of the Ford Super Duty F-550 cab and chassis. The agreement also allows Azure to perform hybrid powertrain conversions on other Super Duty vehicles including F-350 and F-450 models and spans all engine, frame length and regular production options and configurations. It is expected that this could lead to a diesel engine version of the Azure parallel hybrid system using Ford's new 6.7L TC V8 diesel.

According to Azure's Vice President of Current Product Engineering, the initial application for the F-450/F-550 PHEV is utility bucket trucks. Azure will gather additional field data on other potential vehicles and applications to facilitate optimization of the hybrid system. Production of the F-450/F-550 PHEV will likely start in 2014 with a few pre-production units expected in late 2013.³⁵ The Azure/Ford agreement includes a 'ship-thru' provision that permits Azure to place vehicles in the Ford transportation system and allows qualified Ford Commercial Truck dealerships to sell and service the product in key markets in North America.

³⁴ Automotive Insight interview with CTO of Azure Dynamics at HTUF National Conference (October 11, 2011).

³⁵ Buchholz, Kami, SAE Truck & Bus Engineering Online. (December 16, 2011). Future CV products at Ford include new Transit van and plug-in trucks.

4.2.3 BAE Systems

BAE Systems has over 30 years of experience in the development of hybrid-electric drive systems for heavy-duty vehicles. They presently sell both parallel and series hybrid drive components and complete systems for commercial vehicles including heavy trucks and transit buses, and also offer hybrid-electric systems aimed at military vehicles. In order to obtain BAE Systems input on hybrid system experiences and future plans, the study team met with multiple persons from BAE Systems.

BAE's **HybriDrive Series Hybrid System** powers the world's largest hybrid bus fleet, is presently in use on over 3,500 buses, and has traveled over 300 million miles in service. The series design is optimized for transit bus duty cycles that typically have low average speeds and frequent stops. In this type of environment, a series hybrid provides better fuel economy and emission reductions than a parallel solution. BAE offers its series HybriDrive system in two sizes—HDS 200 and HDS 300—and produces its own motor/generator units, battery packs, propulsion control systems, and electric accessory power systems. Key components are as follows:

- The Modular Traction System (MTS) is composed of a traction motor and a traction generator to provide power to the vehicle and recharge the batteries.
 - The brushless AC induction traction motor is liquid cooled with high power-to-weight ratio, and connects directly to a standard drive shaft and rear axle to provide traction power and regenerative braking.
 - The motor incorporates a fixed ratio reduction gear, eliminating the need for a gear shifting transmission. This provides shift-free propulsion for the transit bus; providing a noticeably smoother ride for passengers than traditional diesel or parallel hybrid buses.
 - The traction motor is the sole source of propulsion for the vehicle and is sized accordingly, providing high power and superior low-end torque.
 - HDS 200: 265 HP (200 kW) and 3760 ft-lbs peak, 215 HP (160 kW) and 2790 ft-lbs cont. for vehicles up to 41,000 lb GVW
 - HDS 300: 308 HP (230 kW) and 4979 ft-lbs peak, 241 HP (180 kW) and 3909 ft-lbs cont. for vehicles up to 62,500 lb GVW
 - The combination of the down-sized engine, generator and traction motor occupies an equivalent space claim of a typical engine/transmission unit. This system's design and packaging makes it easily adaptable to multiple bus models and easy to install. The MTS can be installed in-line T-drive, V-drive, or transverse.
- The Energy Storage System (ESS) is based on lithium-ion nano-phosphate technology and uses an advanced battery module design to provide very high

power and energy density in a compact, lightweight enclosure. The system delivers power during acceleration and peak power demands and accepts power (regenerative braking energy) during deceleration.

- The use of lithium-ion technology enables the system to be substantially smaller and lighter than other energy storage options and unlike other technologies, does not require air conditioning to cool the batteries. This contributes to improved fuel economy, reduced brake wear and allows for greater weight capacity for passengers.
- BAE Systems specifically uses a nano-phosphate version of lithium-ion chemistry for its thermal stability. The modular construction enables easy servicing.
- Peak power: ± 200 kW
- DC bus output voltage: 500 - 700 V DC (635 V DC nominal)
- Operating temperature: -40°F to 125°F (-40°C to 52°C); cold-weather kit required below 14°F (-10°C)

The BAE HybriDrive Modular Traction System and Energy Storage System are shown below.

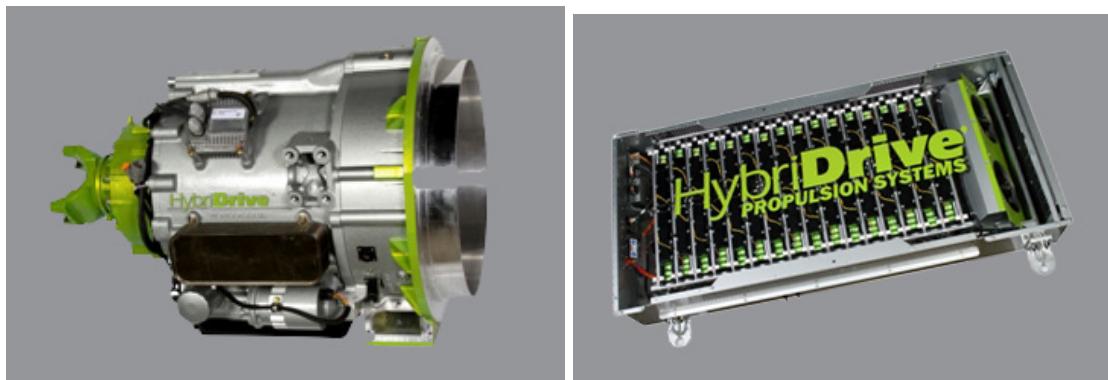


Figure 43: BAE Systems Modular Traction System and Energy Storage System

- The Propulsion Control System (PCS) is the power processing and power management center for the entire HybriDrive system. It works in conjunction with the brain of the HybriDrive system, the System Control Unit (SCU) which provides the system monitoring and control.
 - The PCS and PCU control the optimal flow of power to and from the traction motor, generator and energy storage system.
 - They also enable the overall system performance to be customized to an operator's specific requirements and provide diagnostic information to enhance maintenance of the entire HybriDrive system.
 - Features include:

- Selectable acceleration and regenerative braking settings
 - Onboard diagnostics
 - Optional Electronics Cooling Package (ECP) is available to OEMs
 - SAE 1939 CAN interface
 - System control and vehicle interface electronics mounted externally
 - Optional high voltage output to support electric heater
 - PCS is liquid cooled for superior thermal management and control
- The Accessory Power System (APS) offers two levels of electrification of accessories and includes power electronics options from partial electrification, with engine off function, to full electrification of the platform's accessory loads. HybriDrive® can be configured to further enhance efficiency and performance with either an APS Level 1 or an APS Level 2:
 - **The APS Level 1** provides 28 volt DC electrical power to the vehicle. The unit functions as an electronic alternator, completely replacing the conventional belt driven alternator. It operates by converting power from the hybrid high-voltage DC system directly to 28 volt DC power. The 530 amps of continuous output is more than enough capacity to power all conventional electric loads, such as cooling fans and pumps, plus all hybrid cooling systems.
 - **The APS Level 2** supports full electrification of accessories to further enhance efficiency and performance of your vehicle. APS Level 2 replaces the conventional belt driven alternator and provides 24/28 volt power to support a range of vehicle systems and electronic components (e.g. cooling fans, cooling pumps, and all conventional 28V systems and accessories). The APS also provides 208/230VAC 3-phase power for the electrification of large accessory loads (e.g. air compressors, power steering, and air conditioning). The system enables engine stop/start and electric vehicle (EV) modes.

The BAE HybriDrive Propulsion Control System and Accessory Power System are shown below.

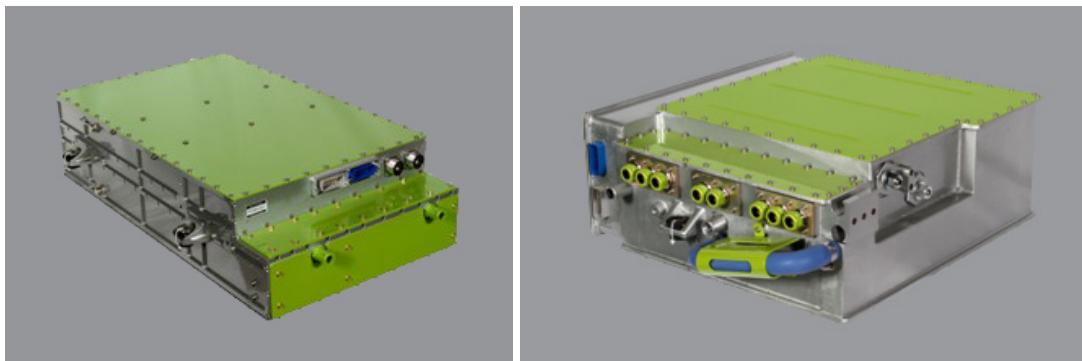


Figure 44: BAE Systems Propulsion Control System and Accessory Power System

The typical installation and component locations for the HybriDrive Series Hybrid system in a transit bus are shown in the figure below.

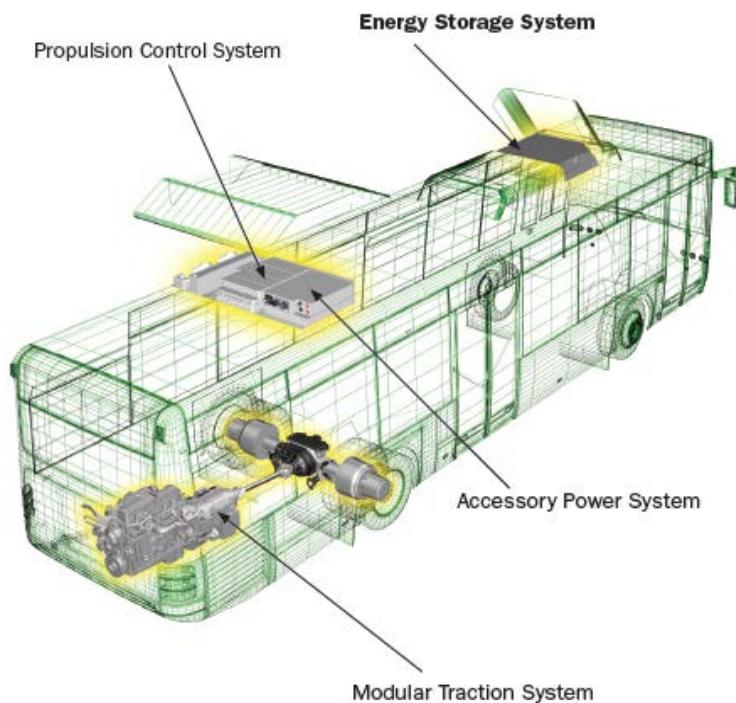


Figure 45: Typical HybriDrive Series Hybrid System Packaging in Transit Bus

Source: Automotive Insight meeting with BAE Systems, September 21, 2011

A comprehensive test conducted at the Altoona Bus Research and Testing Center in Pennsylvania showed that in some cases, BAE Series HybriDrive buses achieved almost double the fuel economy of equivalent conventional diesel buses, and also outperformed competitive hybrid systems in buses as shown in the figure below.

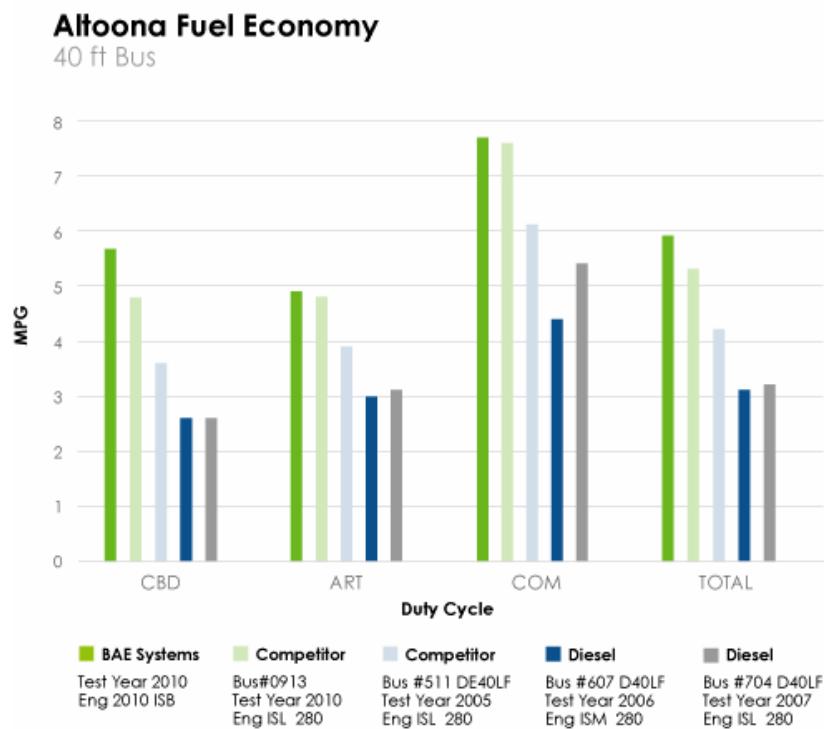
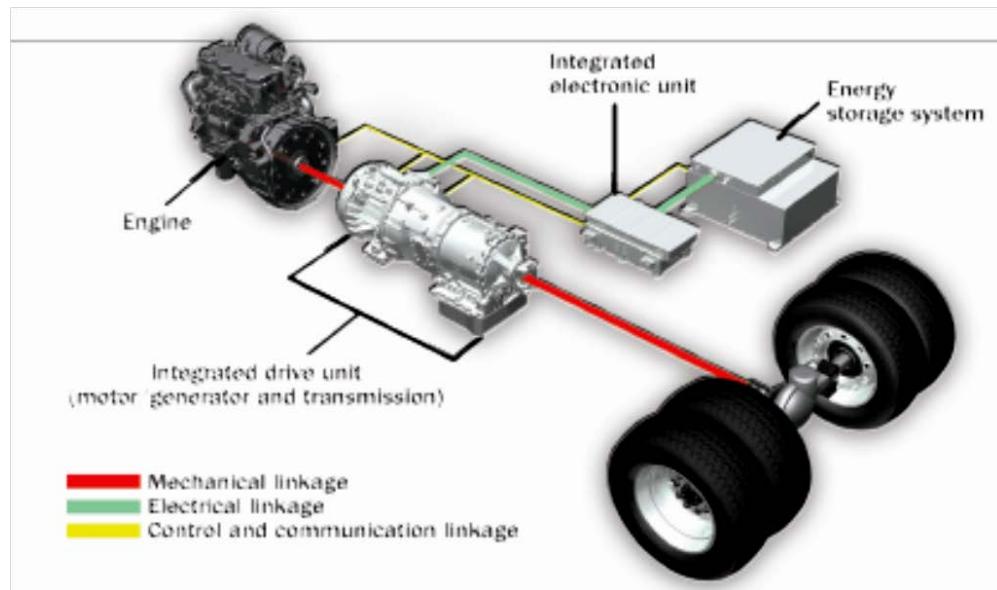


Figure 46: Altoona Fuel Economy Testing of BAE Systems Series Hybrid Transit Bus

Source: BAE Website. Retrieved from <http://www.hybriddrive.com/hybrid-transit-bus.asp>

BAE Systems is now developing a parallel hybrid-electric system design for the commercial heavy-duty truck market. The HybriDrive Parallel Hybrid drive system uses an off-the-shelf Caterpillar CX Series transmission with an electric motor/generator mounted on the input side. This can be installed with minimal impact to the vehicle, and propulsion is enhanced through an optimized blending of engine and electric motor. The system is scalable to meet a wide range of heavy-duty truck platforms, vocations, and duty cycles, and applications include hybrid construction, utility, refuse and delivery trucks. BAE Systems expects to begin production of this system in late 2012.³⁶

³⁶ Automotive Insight meeting with BAE Systems, September 21, 2011.

**Figure 47: BAE Systems HybriDrive Parallel Hybrid Truck System**

Source: Automotive Insight meeting with BAE Systems, September 21, 2011.

There are four models of the HybriDrive Parallel Hybrid system, with a range of power ratings and number of power take-offs (PTOs). Two electric motor variants are available with a choice of four transmissions. BAE notes that the resulting power and torque ratings are up to three times those of other parallel hybrid systems presently being offered.³⁷ These ratings for the four models are shown in the table below.

Table 9: BAE Systems HybriDrive Parallel Hybrid Model Ratings**The HybriDrive® Parallel Product family your power and performance needs**

Product	System		Hybrid		# of PTOs
	Model	Max power kW (Hp)	Max torque Nm (ft-lb)	Max power kW (Hp)	
HDP 600	260 (350)	1015 (750)	70 (94)	400 (295)	1
HDP 700	260 (350)	1700 (1250)	70 (94)	400 (295)	3
HDP 750	260 (350)	1700 (1250)	110 (145)	800 (590)	3
HDP 800	400 (540)	2350 (1740)	110 (145)	800 (590)	3

³⁷ Automotive Insight meeting with BAE Systems, September 21, 2011.

BAE has designed the HybriDrive Parallel System to withstand the demands of the on/off-road environment. The clutch between the engine and electric machine allows the vehicle to be launched electrically without support from the engine. While on a jobsite, it is possible to declutch from the engine and operate equipment on the truck electrically. The system has been designed to interface with engines rated between 300 and 650 hp, whether CNG, diesel, or gas. BAE Systems has seen an average of 30% fuel consumption reduction in testing over a range of duty cycles.

Crane Carrier has expressed an interest in using this BAE hybrid system in their Model LET2 refuse truck, and is presently doing prototype testing in select fleets. A production model is expected in late 2012.³⁸

³⁸ HTUF 2011 Show Times. (October 10 – 13, 2011). BAE Parallel Entering Trials with Crane Carrier.

4.2.4 Eaton Corporation

The Eaton parallel hybrid-electric powertrain system is the most widely used design in medium- and heavy-duty hybrid trucks today, with over 5,000 shipped since its introduction in 2007. In order to obtain information on present and future Eaton hybrid powertrain plans, the study team met with Craig Jacobs, Global Chief Engineer for Hybrid Systems and Architecture at Eaton Corp.

Eaton has been active in the development of electric hybrid powertrains for trucks and buses for over 10 years, as illustrated in the figure below.

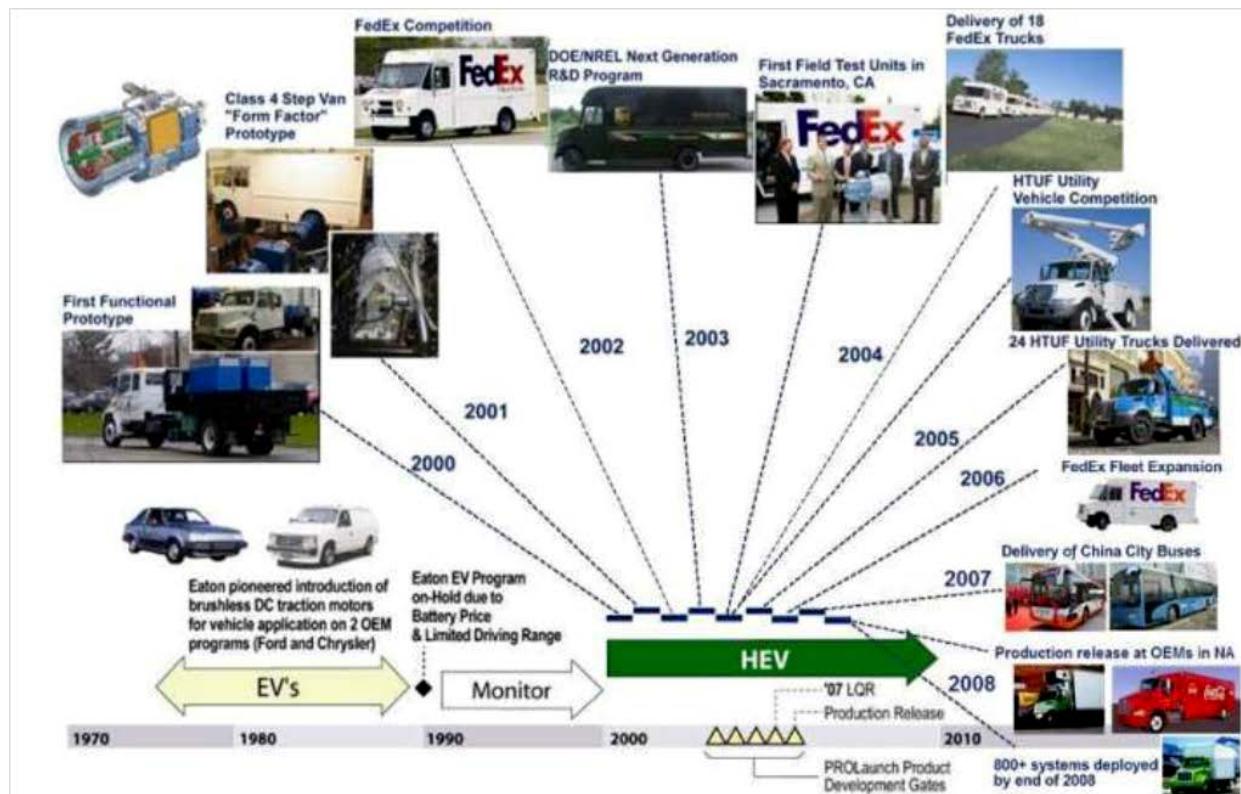


Figure 48: Eaton HEV Powertrain Development History

Source: Cornils, Helene – Eaton Corp. (June 10, 2009). Hybrid Solutions for MD Commercial Vehicles. Retrieved from <http://www.erc.wisc.edu/documents/symp09-Cornils.pdf>

Technical details of the Eaton parallel hybrid-electric drivetrain are as follows:³⁹

- The system uses a dedicated Eaton Fuller 6-speed auto-shift manual transmission that incorporates a Hitachi 44 kW traction motor/generator
- An electrically actuated decoupling clutch disengages the engine from the Hybrid Drive Unit
- The lithium-ion battery pack is produced by Hitachi, and rated at 1.9 kWh
- The associated inverter and controls are integrated into the hybrid drive unit
- A separate hybrid control module is provided with software tailored to each vehicle application
- The engine is provided by the various truck manufacturers and may vary. One commonly used engine is the Cummins 6.7L ISB in-line 6-cylinder diesel.
- Eaton also offers an Auxiliary Power Generator (APG) Inverter for on-board equipment and 120V auxiliary power

The Eaton system diagram is shown in the figure below, along with a picture of the Hybrid Drive Unit.

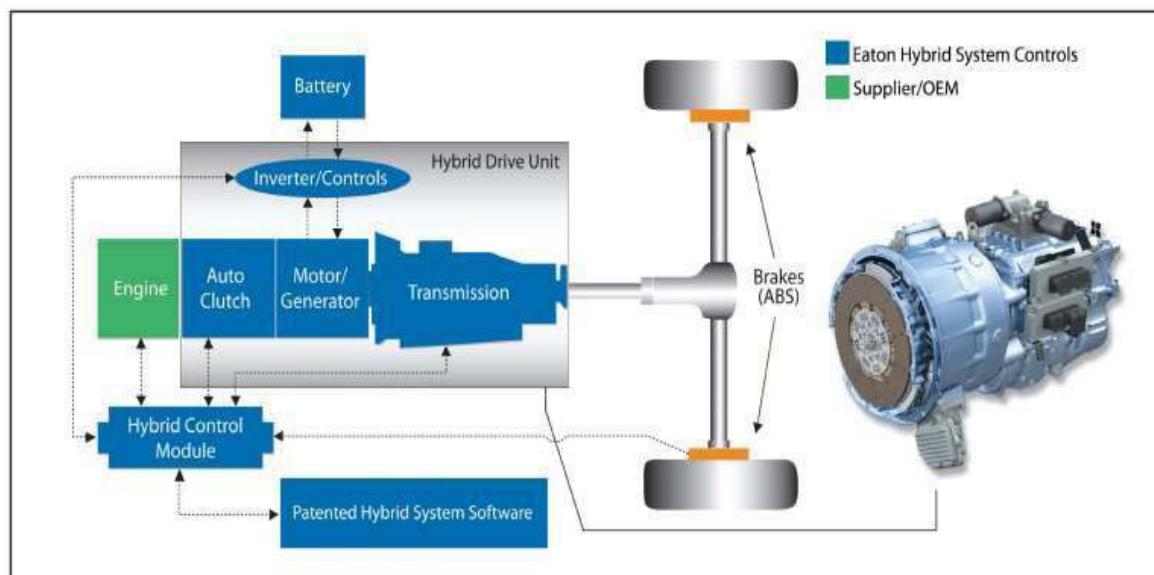


Figure 49: Eaton Parallel Hybrid System Diagram

Source: Cornils, Helene – Eaton Corp. (June 10, 2009). Hybrid Solutions for MD Commercial Vehicles. Retrieved from <http://www.erc.wisc.edu/documents/symp09-Cornils.pdf>

³⁹ Interview. (September 9, 2011). Craig Jacobs, Global Chief Engineer for Hybrid Systems and Architecture, Eaton Corp.

The truck manufacturers that purchase the Eaton system do all of the component packaging, while Eaton assists with the high voltage cable routing and system integration. Eaton also provides field service training on the system to each manufacturer's service technicians, as well as end-customers.

The table below shows the range of truck and bus applications for the Eaton parallel Hybrid Electric (HEV) system, along with the Hydraulic Launch Assist (HLA) and Series Hydraulic Hybrid (SHH) powertrains as of mid-2009. Some of the Pre-production HEV applications on this chart have now entered production, such as the MD school bus.

Table 10: Eaton Production Hybrid Truck and Bus Applications

	Step Van P&D 	City Delivery 	Utility Vehicle 	City Bus 	Shuttle Bus 	School Bus 	Refuse Trucks 
LD Up to 19,500 lb GVW	 HEV SHH	 HEV			 HEV SHH / HLA	 SHH	
MD 19,501 to 33,000 lb GVW	 HEV SHH	 HEV SHH	 HEV	 HEV SHH / HLA	 HEV SHH / HLA	 HEV / HLA SHH	 HEV
HD >33,000 lb GVW		 HEV	 HEV	 HEV SHH			 HLA

-  Production Released
-  Pre-production / Prototype Phase
-  Early Development / Market Research Phase



28

Source: Cornils, Helene – Eaton Corp. (June 10, 2009). Hybrid Solutions for MD Commercial Vehicles. Retrieved from <http://www.erc.wisc.edu/documents/symp09-Cornils.pdf>

The Global Chief Engineer for Hybrid Systems and Architecture at Eaton indicated that the company is working on a next-generation parallel hybrid system that will upgrade the motor from the present 44 kW rating to 60 – 70 kW, along with a larger battery. There may also be a plug-in hybrid version of this system.⁴⁰

The present Hitachi Li-ion battery pack used with the Eaton system is rated at 1.9 kWh and operates at 340V. There are some 12-meter bus applications in China that utilize two of these packs, for a total of 3.8 kWh energy capacity. Eaton plans to introduce a more powerful battery pack in 2012 produced by LG Chem and rated at 5.1 kWh at 350V. Eaton also plans to upgrade the Auxiliary Power Generator option from 120V to 208V 3-phase power in 2012, for additional exportable power capability in applications that require this.⁴¹

Eaton is presently engaged in developing a plug-in hybrid-electric system and has obtained a \$45 million DOE grant to fund this. They have built a prototype Ford F-550 truck with a 23 kWh battery pack, on-board charger, and electric-assist power steering and brakes. This vehicle is presently capable of driving 15 miles on electric power alone, and Eaton is continuing development work. Eaton presently has no plans to utilize blended energy storage packs with ultracapacitors in addition to Li-ion battery cells. The company believes that such designs remain expensive relative to the benefits they offer.⁴²

He believes that the market forecasts of 20-30,000 hybrid trucks per year in the next few years that have been published by Pike Research and Frost & Sullivan are very optimistic. He does not see anywhere near that level of demand at present price levels, or the breakthroughs in technology cost that would be needed to achieve those volumes.⁴³

Eaton believes that a key area of technology development still required to improve hybrid truck acceptance is in electric accessories that would allow additional operation with engine off. At present, the engine must continue idling if there are electrical loads from heating and cooling systems or other devices.

⁴⁰ Interview. (September 9, 2011). Global Chief Engineer for Hybrid Systems and Architecture, Eaton Corp.

⁴¹ Ibid.

⁴² Ibid.

⁴³ Ibid.

4.2.5 General Motors Allison Transmission

The Allison Hybrid EP system features what Allison describes as a two-mode split parallel architecture with a pure mechanical path and a pure electrical path to achieve the highest energy efficiency. This architecture is similar to that used in the Dual-Mode RWD transmission that GM developed with DaimlerChrysler and BMW and used in the Chevrolet Silverado and Suburban and Cadillac Escalade hybrids. This design is well suited for in-city stop-and-go transit as well as long distance highway applications. When operating with 2010 EPA diesel engines, the Allison Hybrid EP system dramatically reduces diesel fuel consumption. Typical fuel economy improves by 20-30% over similar vintage, standard diesel buses (results can vary depending on the duty-cycles.)⁴⁴

When decelerating or stopping, the system uses regenerative braking to convert the vehicle's kinetic energy to stored electric energy. Allison claims that forty percent of the energy to accelerate the bus comes from the braking energy saved.⁴⁵ Regenerative braking also saves on brake maintenance costs. Some Allison hybrid bus customers are reportedly experiencing brake life of 170,000 miles with Allison Hybrids as compared to 55,000 miles with a standard bus.

Allison claims that a bus equipped with the Allison Hybrid EP system can significantly out-accelerate a similar bus equipped with a conventional drivetrain or an alternative fuel system, providing smooth and seamless acceleration. Drivers and passengers are said to prefer the Allison Hybrid to standard buses because the ride is smooth and comfortable.⁴⁶

Allison provides a feature they call HyGain where a transit agency can adjust the acceleration rate to fit their operating requirements, either improving performance or trading performance for additional fuel economy. The range of options is illustrated below.

⁴⁴ Allison Hybrid brochure. Retrieved from <http://www.allisontransmission.com/servlet/DownloadFile?Dir=publications/pubs&FileToGet=SA5983EN.pdf>

⁴⁵ Ibid.

⁴⁶ Ibid.

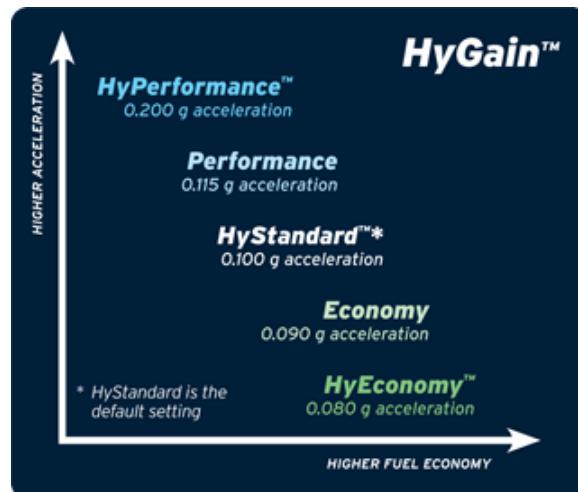


Figure 50: Allison Hybrid EP HyGain System

Source: Allison Hybrid Transmission website. Retrieved January 17, 2012 from <http://www.allisontransmission.com/commercial/transmissions/hybrid-bus/>

Allison Series Hybrid Drive Unit Ratings

- **Allison H 40 EP Drive Unit - *Transit Bus***
 - Continuous: 280 hp (209 kW)
 - Rated Input Torque: 910 lb-ft (1234 N-m)
 - Rated Input Speed: 2300 RPM
- **Allison H 50 EP Drive Unit - *Suburban Coach / Articulated Bus***
 - Continuous: 330 hp (246 kW)
 - Rated Input Torque: 1050 lb-ft (1424 N-m)
 - Rated Input Speed: 2300 RPM

Allison System Components⁴⁷

H 40 EP / H 50 EP Drive Unit

Two power levels with same proven form, fit and function.

- Two-mode parallel hybrid operates automatically as a parallel hybrid or series hybrid
- Continuously variable drive with an infinite number of ratios
- Automatically adjusts ratios to operate at optimum power curves to attain best performance and fuel economy



ESS2 (Energy Storage System)

The latest Nickel Metal Hydride battery cell technology from PEVE is utilized in this second-generation unit.

- Common, high-capacity hardware to handle every bus size
- First generation ESS achieved over 100 million miles of revenue service without any end-of-life battery cell failures
- New technology proven durable and reliable to avoid risks associated with experimental energy storage devices



Fourth Generation Electronic Controls

The latest commercial high-volume, high-quality controller features common hardware to all the latest Allison transmissions and hybrids.



- Greater processing power and memory capability
- Memory expansion allows for further technology evolution
- Fewer electrical connections for greater system durability and reliability
- Full optimization with latest engines
- Allison HyValue™ performance features HyGain™, HyIdle™ and HyTraction™

DPIM2 (Dual Power Inverter Module)

The second-generation unit features more robust internal hardware with enhanced redundancy for greater reliability.

Externally, this unit is fully interchangeable with all prior production units.



⁴⁷ Allison website. Retrieved from <http://www.allisontransmission.com/commercial/transmissions/hybrid-bus/>

4.2.6 ISE Corporation/BLUWAYS

ISE Corporation began developing series hybrid-electric drivetrains in transit buses in the mid-1990s, and delivered its first commercial unit in 2004. ISE manufactures its own drive system, energy storage systems including lithium-ion batteries, ultracapacitors, and blended storage, and control systems. ISE is unique in offering hybrid drive systems powered by gasoline, compressed natural gas, fuel cell, and diesel fuels, as well as all-electric bus systems. Its drivetrains are now used in over 300 hybrid transit buses, and trials are underway on three refuse haulers with the Department of Sanitation for New York City. The assets of ISE Corp. were purchased by BLUWAYS in 2011.

Typical components of an ISE series hybrid drivetrain system for a transit bus include:

- Motive Drive Subsystems—electric drive motors, motor controller, gear reduction system, driveline, and related components.
- Auxiliary Power Units (APU)—engine, electric generator, and related components. Alternative APU concepts offered by ISE include microturbines and fuel cells.
- Energy Storage System—integrated pack of either batteries or ultracapacitors. Monitoring, charging, equalization, and thermal control elements are included with both versions.
- Vehicle Control and Diagnostics—hybrid energy management controllers, dashboard displays, remote diagnostic tools, and related components.
- Electrically-Driven Accessories—electrical power steering and braking systems, air conditioning systems, and related components.

ISE's Li-ion Battery Pack comes in either 110V (A) or 220V (B) configurations, and has a nominal capacity of 2.4 kWh. Each module contains 96 Altairnano 11Ah cells. Specifications are shown below:

- Nominal capacity: 2.4 kWh
- Rated power (continuous/peak): 13 kW / 42 kW
- Rated voltage (nominal/max): A: 110/134 VDC B: 220/268 VDC
- Rated current (continuous/peak): A: 132/400 A B: 66/200 A
- Rated Cycles: 25,000
- End of life: 80% capacity
- L x W x H: 778 x 482 x 366 mm
- Weight: 87 Kg
- Cooling: Liquid

ISE's Ultracapacitor Module is rated at 110V and 0.1 kWh. Each module contains 48 Maxwell Boostcap 3000P ultracapacitors. Specifications are shown below:

- Total energy stored (nominal/peak): 105/125 Wh
- Rated power: 40 kW
- Rated voltage (nominal/max): 110/120 VDC
- Rated current (continuous/peak): 150/400 A
- Cycles: 1 million
- Capacitance: 62 F
- L x W x H: 778 x 482 x 303 mm
- Weight: 51 Kg
- Cooling: Liquid

The ISE Master Control Module is the brain of the Energy Storage System. A 32-bit microcontroller handles all communication and power management for the energy storage module. The Master Control Module contains pre-charge circuitry, main contactors, a 500A-rated current sensor, high voltage/isolation measurement, and a CAN J1939 user interface. Combined with ISE's modular pack design, the Master Control Module allows easy system integration and scalability.

The figure below illustrates an energy storage system containing three ISE Li-ion battery packs plus the master control module.



Figure 51: ISE Li-Ion Battery Packs and Master Control Module

Source: ISE Corp. website. Retrieved from <http://www.isecorp.com/energy-storage/>

4.2.7 Meritor

Meritor is developing a diesel-electric hybrid system for Class 8 trucks that is similar to a Power-split design in that it combines Parallel and Series Hybrid design elements. Meritor calls this a Multi-Mode Hybrid (formerly Dual Mode). There are two electric machines between the engine and the drive wheels, and a coupling between them that can be opened to decouple the engine from the driveline and primary traction motor.

This Meritor hybrid powertrain can operate in either Series or Parallel Mode.

- The system runs in Series mode at speeds below 50 mph, with the engine decoupled from the driveline. Vehicle propulsion is delivered entirely through an electric motor with power from lithium ion batteries. These batteries are recharged through regenerative braking and/or an engine-driven generator. The engine can be on or off depending on the battery state-of-charge (SOC).
- At higher speeds above 50 mph, the system switches to Parallel mode with the engine on to provide primary drive power. The electric motor contributes additional power as needed based on driveline speed, hybrid drive gear ratios and truck load requirement. The motor can also regenerate power to the battery under braking.
- The batteries can also provide up to eight hours of continuous power for hotel loads during overnight rest periods, which eliminates the need for engine idling or other redundant anti-idling systems.

The system operating configuration for these two modes is shown in the figure below.

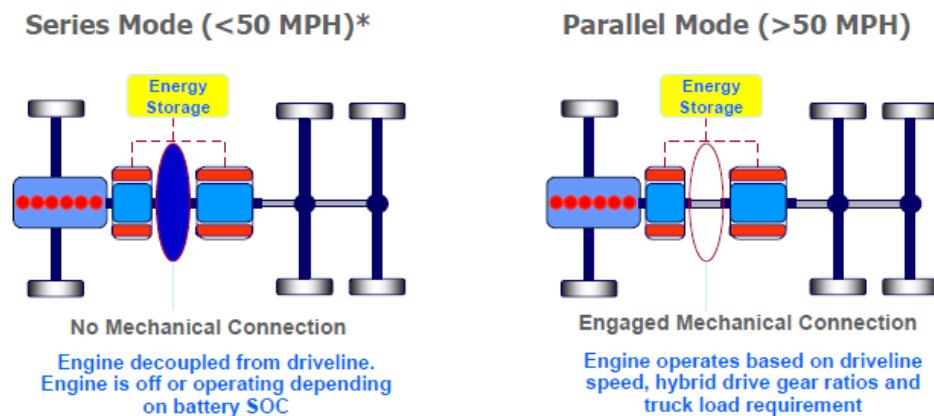


Figure 52: Meritor Class 8 Multi-Mode Hybrid Operating Modes

Source: Hicks, Brad, ArvinMeritor. Class 8 Electric Hybrids – Opportunities and Challenges. SAE Hybrid Vehicle Technologies 2010 Symposium.

The functional and design characteristics of the Meritor Multi-Mode system are compared to conventional Parallel and Series truck hybrid systems in the figure below.

Parallel	Dual Mode	Series
<ul style="list-style-type: none">• 25-80 kw-hr motors• Transmission based• Emission reduction related to fuel economy• Limited production• Limited electric mode 	 <ul style="list-style-type: none">• Combines benefits of Series and parallel• 150-200 kw-hr Motors• No conventional transmission• Zero emission mode• Proof of concept• Full electric mode	<ul style="list-style-type: none">• 200-450 kw-hr Motors• No conventional transmission• Zero emission mode• Production in buses• Proof of concept• Full electric mode

Figure 53: Hybrid Systems for Class 8 Trucks

Source: Hicks, Brad, ArvinMeritor. Class 8 Electric Hybrids – Opportunities and Challenges. SAE Hybrid Vehicle Technologies 2010 Symposium.

Meritor began fleet testing on this Multi-Mode hybrid system in the Wal-Mart fleet in 2009, and has not yet announced plans for series production.

4.2.8 Odyne (DUECO)

Odyne has recently introduced a plug-in hybrid electric powertrain in a standard chassis-cab platform that is targeted at work trucks over 14,000 lb GVW that need auxiliary power, such as bucket trucks and digger derricks in utility fleets. It is designed to integrate through the PTO, requiring no modifications to the conventional engine and transmission. The components are bundled into modules which package into areas normally open on work truck chassis, which means it can easily be retrofitted to trucks in service. The battery can be sized to power the hydraulic lift mechanism plus on-board electrical accessories for the duration of a typical workday and then be recharged overnight at the vehicle's home base.⁴⁸

The Odyne PHEV system diagram is shown in the figure below.

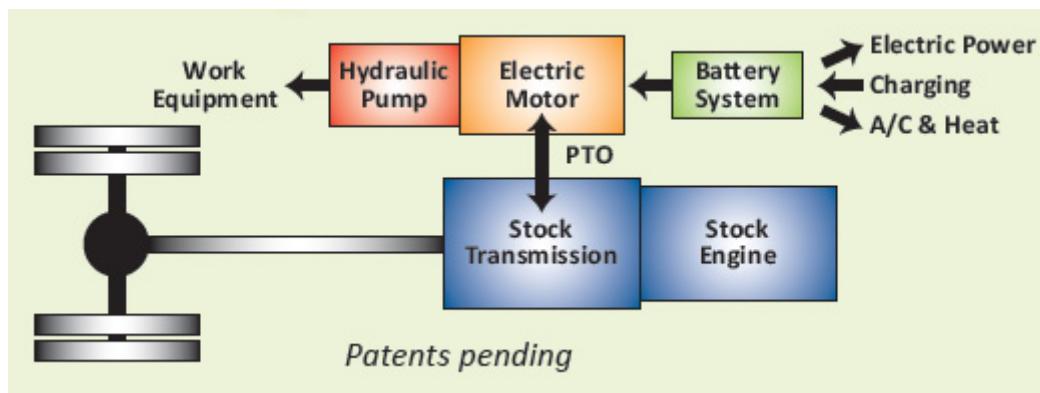


Figure 54: Odyne PHEV Work Truck System Diagram

Source: Odyne website. Retrieved November 13, 2011 from <http://www.odyne.com/hybridsystems.html>

Features and specifications of the Odyne PHEV truck system are as follows:⁴⁹

- Remy HVH250 traction motor rated at 160 kW peak output and 440 N·m peak torque
- Johnson Controls (JCI) Li-ion battery pack – single 14 kWh or double 28 kWh pack available (same pack used in Ford Transit Connect EV)
- Phoenix International PD300 power inverter operating at 300V
- LCD info panel included to show operator the battery SOC, voltage, and amperage usage

⁴⁸ Interview. (October 12, 2012). VP Operations for Odyne
⁴⁹ Ibid.

- Provides up to 50 hp of launch assist when driving
- Regenerative braking energy recapture
- Up to 8 hours of job-site power with the 28 kWh battery configuration
- Up to 7 kW of exportable power for other job-site power needs
- Optional hydronic heater and electric air conditioning units to heat and cool the truck cab during engine-off operation
- Fuel economy improvements of up to 50% or greater, compared to traditional diesel/gas engines
- Quiet operation with zero or significantly lower emissions at the job site
- Engine can recharge battery in field if depleted, then shut off again.

The following figure shows how these modular PHEV components package on a typical medium-duty truck frame.

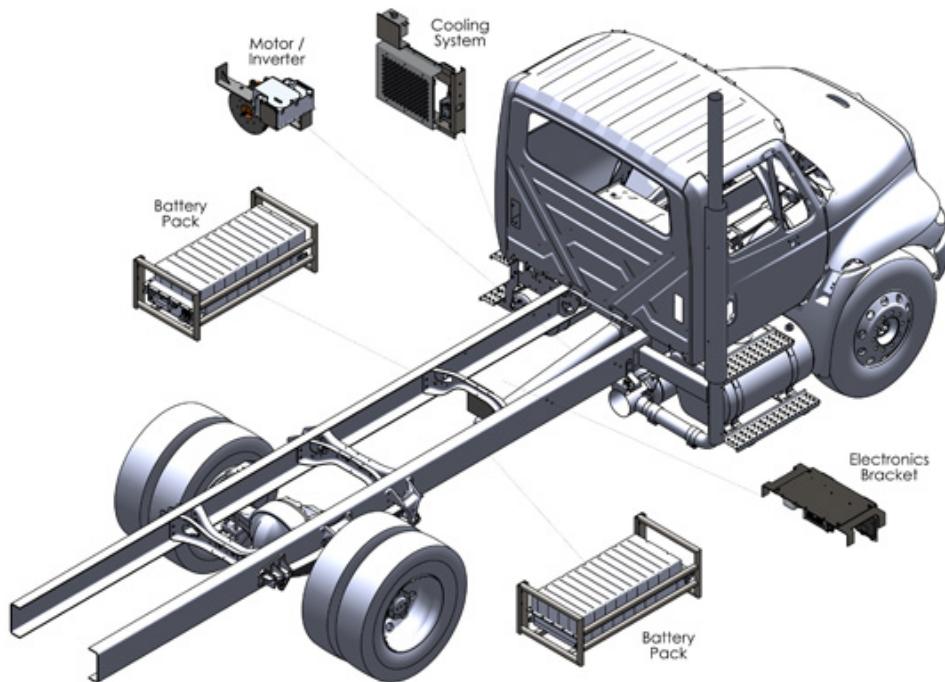


Figure 55: Odyne PHEV Truck Modular Component Packaging

Source: Odyne website. Retrieved November 13, 2011 from <http://www.odyne.com/hybridsystems.html>

The following additional comments on the Odyne PHEV system came from the VP of Operations at Odyne:⁵⁰

- The system can provide fuel savings of 1750 gal/yr assuming 250 work days, each having 2 hours of driving and 4.5 hours of electric mode operation.
- Project up to \$2,000 in annual maintenance savings due to the greatly reduced engine usage, as well as additional brake life due to regeneration.
- Typical recharging cost for the battery pack is \$2.50 per day, based on 25 kWh @ \$0.10 per kWh.
- Optional hydronic heater is offered that runs on diesel fuel and heats the water circulating through the heater core to provide cab heat when the engine is off.
- Optional electric air conditioning system is available to cool the cab during engine-off periods. It has somewhat less capacity than the OEM unit, but maintains temperature once the cab is cooled down.
- Odyne offers customers an optional on-board telematics DAQ system with a data logger that allows remote monitoring and system updates.
- Odyne installs this system into trucks produced by parent company DUECO and is paid on a transfer price basis. There are no plans yet to offer to other manufacturers, but they could since the system plugs into an industry-standard interface at the PTO.
- The company hopes to sell 100 of these vehicles in 2012.

⁵⁰ Interview. (October 12, 2012). VP Operations for Odyne

4.3 Market Forecasts

The primary market for MD and HD diesel hybrid trucks and buses to date has been fleet operators. Fleet adoption has been enabled by route predictability, existing infrastructure including central parking/depot, and corporate sustainability efforts by the larger fleet operators. Commercial implementation will also be driven by the new fuel efficiency regulations for MD and HD vehicles beginning in 2014, increasing availability of hybrid vehicles across all truck classes, and rising fuel prices which improve economic payback for hybrids.

Cumulative U.S. heavy-duty hybrid truck sales for 1999-2010 totaled about 11,000 units, or just 0.2% of total HD truck sales over the same period, as shown in the figure below. By way of comparison, alternative fuel HD truck sales were 145,000 units during the same period, or over 13 times that of HD hybrid trucks but still just 3.0% of total HD truck sales. Light-duty hybrid vehicle sales totaled 1.9 million units for 1999-2010. Despite the availability of 32 unique LD hybrid vehicle models in the U.S. market in 2011, sales of 269,000 units totaled just 2.1% of all LD vehicles sold in the U.S.

Cumulative U.S. Sales (1999-2010)

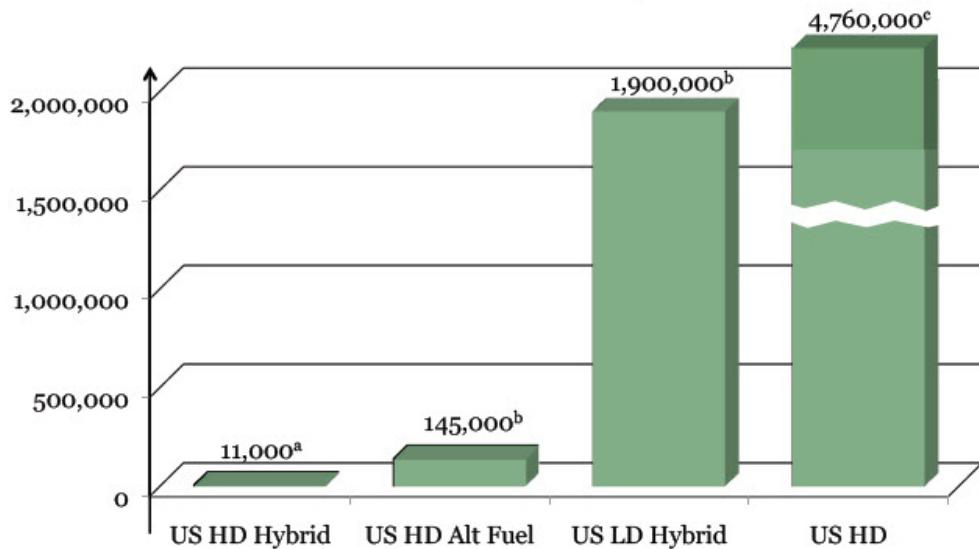


Figure 56: Cumulative Hybrid and Heavy-Duty Truck Sales, 1999-2010

Source: Frost and Sullivan (2010). Quoted by Derek Matthews of BAE Systems in Challenges Facing the Harmonization of Hybrid HD Vehicles and HD Engine OBD, *HTUF National Conference*.

According to a 2011 study done by Pike Research, the global market for hybrid electric, plug-in hybrid and battery electric medium- and heavy-duty trucks is projected to reach 100,000 annual vehicle sales by 2017 as shown in the figure below.⁵¹

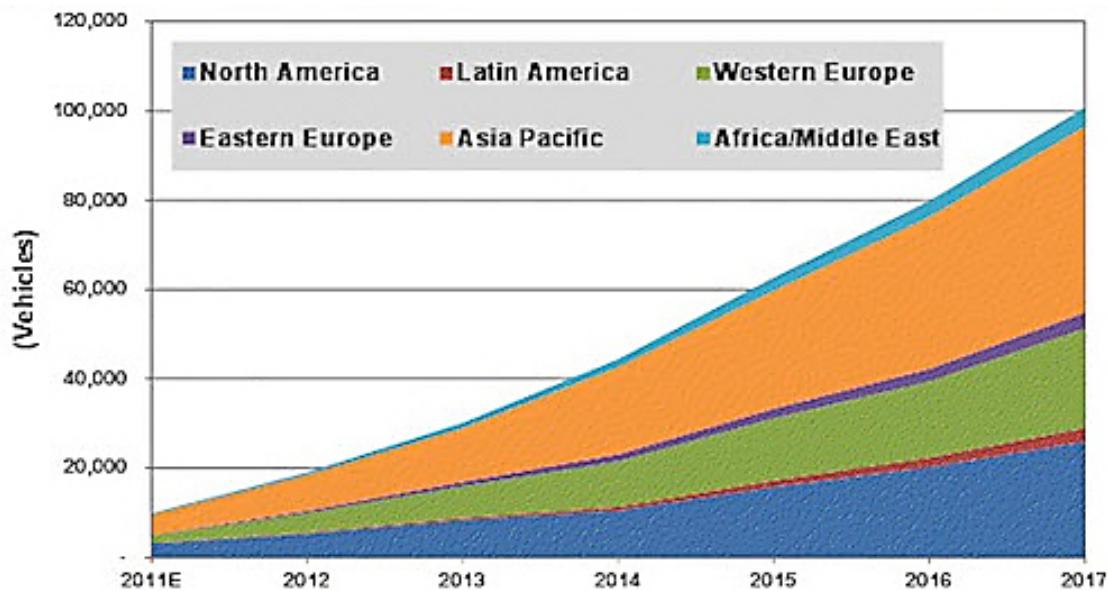


Figure 57: Projected Global Sales of HEV/PHEV/BEV Medium and Heavy Trucks

Source: Hurst, Dave and Wheelock, Clint of Pike Research. (3Q 2011). Hybrid Medium and Heavy Duty Trucks and Buses

⁵¹ Hurst, Dave and Wheelock, Clint of Pike Research. (3Q 2011). Hybrid Medium and Heavy Duty Trucks

Pike Research forecasts that North American (NA) MD and HD hybrid truck sales will grow to nearly 4% of all NA truck sales by 2017, as shown in the figure below.

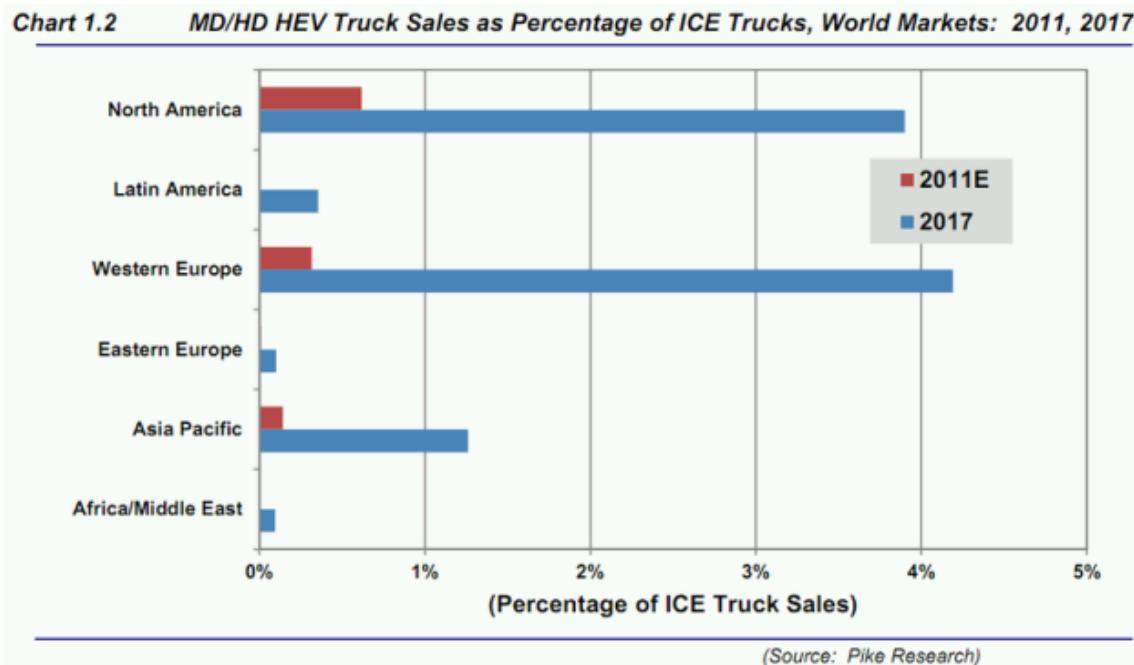


Figure 58: Pike Research Forecast of MD/HD HEV Truck Sales, World Markets: 2011, 2017

Source: Hurst, Dave and Wheelock, Clint of Pike Research. (3Q 2011). Hybrid Medium and Heavy Duty Trucks and Buses

There was a lack of consensus regarding the size of the future hybrid truck market among both the manufacturers and fleet customers that were interviewed for this study. Some felt that the Pike Research and Frost & Sullivan forecasts through 2017 are very optimistic. There is still significant concern over the lack of viable business case for hybrid trucks, whether established through operating economies or government purchase incentives. The recent expiration of some Federal incentives will not help future market demand, even though some state incentives such as California's HVIP program remain in place.

China is expanding initiatives to get electrified trucks and buses into their domestic market. In 2010, there were more than 1.4 million commercial medium- and heavy-duty trucks and buses sold in China. U.S. medium- and heavy-duty truck sales were around 800,000 units in 2005-6, but dropped to less than half this level in 2009-10 due

to the recession in the U.S.⁵² It is expected that China truck sales will continue to be two-three times that in the U.S. market. If either hybrid-electric or electric trucks capture just 1% of the Chinese market, then total volume could exceed the U.S. market volume for electrified trucks. If U.S. heavy-duty vehicle and hybrid system manufacturers are able to capture some of this business, the additional volumes could help to reduce system costs through a larger amortization base. As a result, CALSTART has created the US-China Clean Truck and Bus Technology Forum (China Clean Truck) in partnership with the Dept of Commerce to link the US industry with the prime potential partners for advanced trucks and buses in the Chinese market.⁵³

⁵² R. L. Polk & Co.

⁵³ Van Amburg, Bill. (October 11, 2011). Advanced Truck Market Opportunities in China. Presentation to HTUF National Conference.

5.0 Customer Experience with Diesel-Electric Hybrid Truck and Bus Powertrains

Synopsis

Some truck and bus fleets have been testing diesel-electric hybrid vehicles in low volume since the late 1990's. Hybrid fleet penetrations have increased in the last five years, due in large part to government incentives, rising fuel prices, the promise of 30 – 50% fuel efficiency improvement, and the availability of a wider array of hybrid trucks in the market. Major applications of diesel-electric hybrids today are delivery vehicles, urban buses and utility trucks.

The table below summarizes the fleet experiences with hybrid vehicles as provided by the fleet managers interviewed for this study.

Table 11: Hybrid Fleet Manager High Level Interview Summary

Company	<u>UPS</u>	<u>FedEx</u>	<u>Coca-Cola Enterprises</u>	<u>King County Metro Transit</u>	<u>Verizon</u>
Diesel-Electric Hybrid Fleet Size	380	367	699	468	13
Application	Delivery Vehicle (Step in Van)	Delivery Vehicle (Step in Van)	Delivery Vehicle (Tractor Trailer)	Urban Bus	Bucket Truck
MPG Improvement	Neg. to 40%	3-5%	12-35%	30-50%	N/A
Gov't Funded Purchases	Yes	Yes	Yes	Yes	No
Maintenance Reduction	~50%	<25%	Improvement	~10%	TBD
Business Case Demonstrated	No	No	No	Yes	No
Top Product Wants	Smaller Engine Series Hybrid; PHEV or EV	Smaller Engine Series Hybrid; PHEV or EV	PHEV or EV	Extended electric range	Lower Cost Battery; EV

Source: Automotive Insight.

These fleet managers provided the following feedback on actual fuel economy, maintenance, and driver training.

- Actual fuel savings have fallen short of expectations in most urban bus and delivery vehicle applications. Route selection for hybrid delivery vehicles plays a big role in fuel savings realized, so fleet managers are learning to assign hybrids to route where they will be most effective. An unexpected impact has been new diesel emissions systems that must keep the engine on to regenerate particulate traps, taking away from electric-only operation for the hybrid. Driver behavior also impacts actual fuel savings.
- Maintenance savings have been significant, if sometimes less than anticipated. For instance, improved reliability allowed King County Metro Transit to reduce its staff of mechanics by 10%. Battery durability has also been significantly better than expected across all vehicle applications.
- Drivers generally like the hybrids, finding that they are easy to drive, offer equivalent or better performance, and may be less fatiguing. Getting greatest benefit from hybrids requires training so that drivers understand how best to operate their new vehicles. Driver training is provided by both the fleets and the powertrain manufacturers. In addition, Freightliner has recently introduced a hybrid system status gauge that coaches the driver to maximize the effects of regeneration and reduce fuel consumption.

Favorable business cases for purchase of diesel-electric hybrids rely upon government incentives, projected savings in fuel costs and maintenance reductions to offset purchase penalties. Most fleet purchases have leveraged significant government funding to pay for part or all of their hybrid purchases, including: American Recovery and Reinvestment Act (ARRA) through the Environmental Protection Agency's Diesel Emission Reduction Act (DERA), U.S. Department of Energy through its Clean Cities program, and various state and local government programs. This is now under increasing pressure due to non-renewal of Federal "stimulus" programs and improvements to conventional diesel fuel economy -- some fleets believe that conventional diesel engines have significantly closed the gap to diesel-electric hybrid fuel economy.

The fortunes of the major diesel-electric hybrid applications are expected to diverge based upon economic factors. Delivery vehicles typically do not accumulate enough mileage for fuel economy benefits to translate into compelling fuel savings. Although, fuel savings would be greater for a fleet-optimized hybrid-series rather than parallel with smaller displacement diesel engine--fleet operators do not believe that these preferred vehicles will be offered because of low hybrid sales volumes and manufacturer focus upon conventional diesel vehicle emissions compliance. One fleet executive's opinion is therefore that "the hybrid has run its course." Most major fleets

are testing alternative technologies including battery electric delivery vehicles, sometimes as a large proportion of their fleets but sales volumes are currently also limited by the marginal business case.

Urban bus hybrid applications are expected to continue to grow. Bus fleets are projected to increase their purchases of diesel-electric hybrids based upon improved fuel economy, increased reliability and reduced maintenance, but at a pace slowed by reduced Federal incentives. Utility trucks can achieve greatest efficiency with a plug-in hybrid powertrain, and will likely be hybridized more rapidly if battery costs decrease. Benefits include significant fuel savings, available exportable power, and improved stability of the aerial platform.

5.1 Customer Experience

Customer experience with diesel-electric hybrid truck and buses was investigated through interviews with fleet executives and a comprehensive survey of literature and research. The interviews were conducted with executives responsible for several of the largest commercial fleets of medium trucks and buses, including Coca-Cola Enterprises, Verizon, UPS, FedEx and King County Metro Transit. Additional input on fleet experience was gathered from a separate meeting with BAE as a major supplier of hybrid powertrains to the medium truck and bus markets.

The larger fleet operators have had about a decade of experience with hybrid electric vehicles. In most cases, the hybrid electric component of their fleets has been built up gradually over a number of years. This practice is reinforced by the long useful life of commercial vehicle assets: for instance, a bus may routinely be kept in service for 16 years, while the electric drive components of trolleys may be recycled into the replacement trolley car bodies. In many cases, diesel-electric hybrid and conventional diesel powered vehicles from the same vehicle manufacturer are being run concurrently or the hybrid vehicles were built through conversion of a portion of the conventional diesel powered fleet. This parallel operation places fleet operators in a position to compare and contrast technologies and comment upon how these technologies have evolved over time.

Although diesel-electric hybrid sales volumes are low, a variety of hybrid truck and bus models are now available to the fleet operator. The number of entries has grown as OEMs have met niche needs for important customers, hedged against market uncertainty, and reacted to government incentives and regulatory requirements.

5.2 Major Fleet Applications and Duty Cycles

The larger truck and bus fleets have been testing diesel-electric hybrids since the late 1990's. Fleet managers share insights through conferences and events such as HTUF and the American Public Transit Association Expo, as well as through informal conversation and networking. As a result, the optimum duty cycle and requirements for efficient hybrid operation are commonly shared. Major applications of diesel-electric hybrids are delivery vehicles, urban bus and bucket trucks.

Delivery Vehicles

Package, beverage and general urban delivery is an application well suited to diesel-electric hybrid vehicles because of the opportunity for regenerative braking afforded by repetitive stop-and-go driving. For instance, the Staples' fleet completes 48-52 stop-and-go deliveries per truck per day,⁵⁴ while the Coca-Cola Enterprises fleet typically completes 15-20 deliveries per truck per day.⁵⁵

UPS was the first package delivery company to introduce a hybrid electric vehicle into daily operation with a research program in early 1998.⁵⁶ Coca-Cola Enterprises has been researching hybrid technology since 2001.⁵⁷

Fleet experience with hybrids is significant. Coca-Cola Enterprises operates the largest commercial fleet of diesel-electric hybrids with 699 vehicles.⁵⁸ FedEx has 9.5 million miles of experience from a hybrid fleet of 367 trucks,⁵⁹ while UPS has a hybrid fleet of 380 trucks.⁶⁰ Because the diesel-electric hybrids are versions of vehicles already in the fleet operators' pools, the fleets have had considerable basis for side-by-side comparisons. Examples of the UPS and FedEx delivery vans that utilize a Freightliner

⁵⁴ Simon, Chad. (March, 2011). Staples Fleet Tests Diesel-Electric Viability, Business Fleet. Retrieved from <http://www.businessfleet.com/Article/Print/Story/2010/03/Staples-Fleet-Tests-Diesel-Electric-Viability.aspx>

⁵⁵ Interview. (December, 2011). Director of Fleet Operations – North America, Coca-Cola Refreshments.

⁵⁶ Press Release. (August 2007). UPS Expands its Alternative Fuel Vehicle Fleet with New Order for 130 Hybrid Electric Delivery Trucks. Retrieved from

http://www.gladstein.org/index.php?option=com_content&view=article&id=236:ups-expands-alt-fuel-fleet-with-130-hybrid-electric-delivery-trucks&catid=13:gna-news&Itemid=80

⁵⁷ Shelly Mika. (July 2009). Coca-Cola Enterprises Invests Big in Hybrid Trucks. Retrieved from <http://www.worktruckonline.com/Article/Print/Story/2009/07/Coca-Cola-Enterprises-Invests-Big-in-Hybrid-Trucks.aspx>

⁵⁸ Ibid.

⁵⁹ Interview. (September, 2011) Vice President of Global Vehicles, FedEx.

⁶⁰ Interview. (September, 2011). Director of Vehicle Engineering, UPS.

Custom Chassis configuration with the Eaton Hybrid system are shown in the figure below.



Figure 59: Diesel Hybrid Delivery Vans by Eaton/Freightliner Customer Chassis

Source: Shelley Mika. (August, 2007). UPS Trademark Brown Delivery Trucks Go Green, Work Truck Online; U.S. Department of Energy. (August, 2009). FedEx Converts Delivery Trucks to Hybrids, Delivery Services Fleet Experiences

Fleets have phased hybrids into their pools as a part of their mix of replacement vehicles or as a component of fleet growth planning. Diesel-electric hybrid vehicles have been added either by converting diesel powered vehicles already in the fleet or by purchasing new diesel-electric hybrid powered vehicles. In either case, the powertrain configuration is usually a conventionally-sized diesel powertrain installed in parallel to an electric motor/generator/battery.

FedEx and UPS represent a typical implementation of a diesel-electric hybrid powertrain for the package delivery segment. Both fleets employ Class 4 Freightliner Custom Chassis vans fitted with a 200-horsepower Cummins engine and Eaton electric motor/generator using lithium-ion batteries. These retrofit conversions were performed upon 2000 and 2001 model trucks with accumulated mileage of 300,000 to 500,000 miles.⁶¹ Staples employs an Isuzu truck fitted with a 5.4L Isuzu diesel along with the bolt-on electric motor/generator.

Coca-Cola Enterprises utilizes larger diesel-electric hybrid tractor trailers for beverage delivery. (Coca-Cola Enterprises is moving away from the traditional “straight trucks”

⁶¹ U.S. Department of Energy. (August, 2009). FedEx Converts Delivery Trucks to Hybrids, Delivery Services Fleet Experiences. Retrieved from http://www.afdc.energy.gov/afdc/progs/fleet_exp_app.php/DELIV

due to ergonomic issues.) About 75% of the fleet of Coca-Cola Enterprises is single-axle tractors with 35 foot trailers; the remainder attaches shorter 28 foot trailers to the tractor for urban delivery.⁶² The Kenworth T370 diesel-electric hybrid tractors are powered by the Paccar PX6 engine⁶³ with an Eaton electric motor/generator. An example is shown in the figure below.



Figure 60: Coca-Cola Enterprises Hybrid Tractor Trailer

Source: Shelly Mika. (July 2009). Coca-Cola Enterprises Invests Big in Hybrid Trucks, Work Truck Online.

Commercial fleets have found that route optimization is critical to reaping the potential fuel economy advantages of diesel-electric hybrid trucks. For instance, according to UPS, the ideal daily route is 100 miles, comprised of 10-12 miles on highway to the delivery zone, 80 miles of densely spaced stop-and-go deliveries, then 10-12 miles of highway back to the lot; the highway segments are important to provide adequate time for emissions system regeneration. Route optimization is complex, as UPS manages 6,900 routes.⁶⁴

At FedEx, optimal assignment of vehicles to routes is the role of the Asset Management Department. Diesel-electric hybrids are typically assigned to the shorter, stop-and-go routes but, while this strategy optimizes overall fleet fuel economy, it does not fully capture the potential improvement because routes are generally much shorter than

⁶² Interview. (December, 2011). Director of Fleet Operations – North America, Coca-Cola Refreshments.

⁶³ Press Release. (September, 2008). Kenworth Expands Hybrid Offerings, Introduces New T370 Hybrid Tractor Targeted at Local Haul Applications. Retrieved from

http://www.kenworth.com/6100_pre_mor.asp?file=2332.

⁶⁴ Interview. (September, 2011). Director of Vehicle Engineering, UPS.

optimal for emissions system regeneration (routes in New York, Chicago and Los Angeles are typically only 10-20 miles).⁶⁵

Urban Buses

Urban bus transportation is an ideal application for diesel-electric hybrids because of the continual stop-and-go environment. The typical route is stop-and-go in the city duty cycle, with some highway mileage from garage to route. Total lifetime mileage for an urban bus is 200,000 – 300,000 miles; planned lifetimes are about 12 years but budget considerations often extend lifetimes to 15-16 years or more.⁶⁶

Fleet experience with hybrids is significant. King County Metro Transit has 468 diesel hybrid buses. The largest diesel-electric bus fleet is New York Metro Transit Authority with 1,171. Because the diesel-electric hybrids are versions of vehicles already in the fleet operators' pools, they have considerable basis for side-by-side comparisons.

City buses are typically 40 foot long in non-articulated configuration and 60 foot long in articulated configuration. Hybridization is most commonly performed by Eaton or BAE Systems. Examples are shown in the figure below.



Figure 61: Diesel Hybrid Buses by BAE/New Flyer – King County, Washington Metro

Source: Mike Meredith. (2004). First GM Hybrid Transit Buses Go To Work, *MSN Autos*; Dana Hedgpeth. (May, 2011). Metro Adding More Hybrid-Electric Buses to Its Fleet, *The Washington Post*.

Fleets have phased diesel hybrids into their pools as part of their replacement mix for end-of-life vehicles. As conventional diesel vehicles have been replaced, unique local

⁶⁵ Interview. (September, 2011) Vice President of Global Vehicles, FedEx.

⁶⁶ Interview. (September, 2011). Vehicle Maintenance Manager, King County Metro Transit.

requirements have driven technological innovation and diversification of the products available. For instance, King County Metro Transit buses travel through a 1.3 mile tunnel with limited ventilation under Seattle: this element of the duty cycle resulted in a requirement that King County Metro Transit diesel-electric hybrid buses be capable of operation in an electric-only “Hush” mode.⁶⁷

A number of school bus fleets have conducted pilot programs on hybrid buses, and volumes are starting to increase as Thomas Built (Daimler Group) has introduced production hybrid bus models. These buses can employ their electric motor for low speeds during residential area driving and the diesel engine for higher speeds and freeway driving.



Figure 62: Diesel Hybrid School Bus – Sigourney Community School District, Idaho

Source: Hybrid School Buses Hit the Road; Researchers Test Their Performance, *Science Digest*. (2008)

Bucket Trucks

Bucket trucks include an aerial boom that can raise an operator for maintenance of communications lines, tree trimming and other aerial tasks. The duty cycle typically involves a relative short drive to a work site and then operation of the on-board equipment for hours at a time. This normally requires that the engine be run to drive a hydraulic pump and/or electric generator. This makes these trucks a good candidate for diesel-electric hybrid technology. The hybrid powertrain can be used not just to improve over-the-road fuel economy, but to provide sufficient power from the battery to support the day's operation of the aerial boom on battery power only, without fuel consumption or vibration from the vehicle's diesel powertrain.⁶⁸ The battery may also provide exportable power for operation of power tools at a jobsite.

⁶⁷ Ibid.

⁶⁸ Interview. (September 2011). Program Manager, Verizon Fleet Sustainability.

Some diesel-electric hybrid bucket trucks are capable of hybrid operation, but daily mileage is typically limited so as to minimize operator time traveling to/from job sites. The vehicle's power take-off drives a generator to charge the battery. Representative trucks used as part of a one year PG&E study had capacity for power generation of up to 25 kilowatts.⁶⁹



Figure 63: Diesel Hybrid Bucket Truck -- Cox Communications

Source: Nesi, Ted. (Nov., 2008). Cox, Verizon Add Hybrids to Vehicle Fleets, *Providence Business News*

⁶⁹ PG&E. (August, 2007). PG&E Participates in Hybrid Pilot Program. Press release retrieved from http://pge.com/about/news/mediarelations/newsreleases/q3_2007/070808.shtml

5.3 Fleet Fuel Economy Experience

Most commercial fleets are taking aggressive action to improve fuel economy. Idle reduction, improved powertrains, telematics, and weight reduction are the most popular routes to increasing fuel economy, as shown in the figure below that was presented at the 2011 HTUF National Conference. High efficiency powertrains such as hybrid electric vehicles and battery electric vehicles are being investigated by about 40% of these fleets.

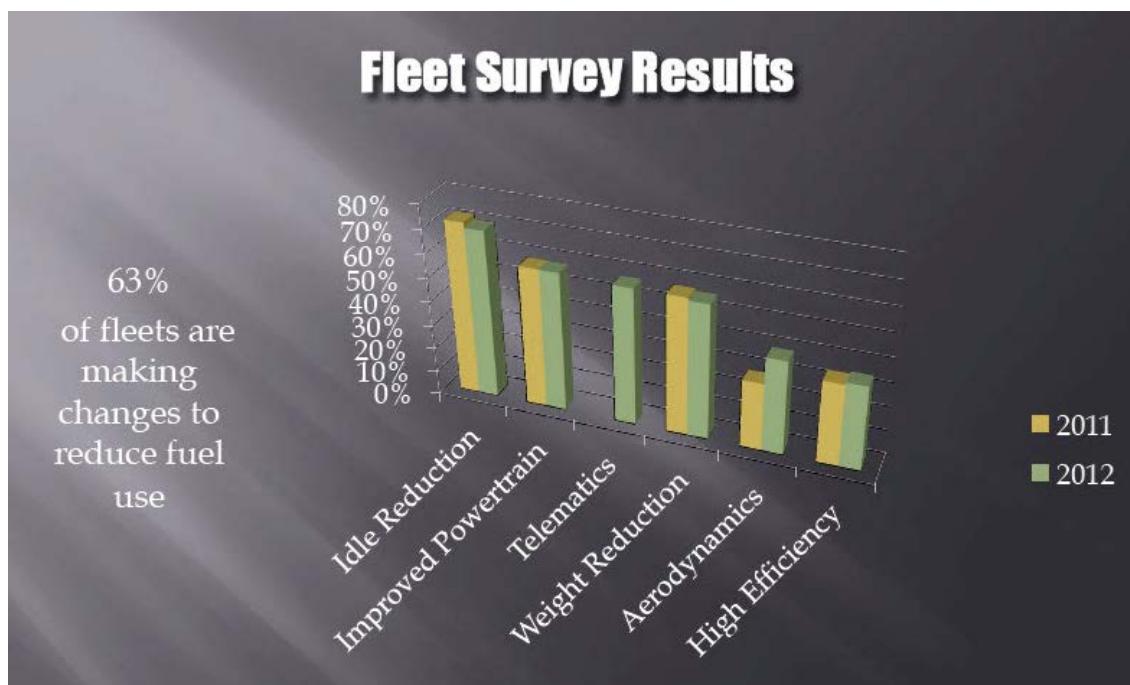


Figure 64: Fuel Economy Improvement Actions Being Pursued by Fleets

Source: Sumrall, Doyle. (October, 2011). Market Assessment, *HTUF National Conference*. Retrieved from http://calstart.org/Files/Presentations/HTUF_2011/Market-Assessment-Doyle-Sumrall-NTEA.pdf

Fuel Economy Expectations

Incorporation of hybrids into delivery vehicle fleets has been fueled by expectations for improvement to fuel economy of 30% - 60% compared to conventional diesel powertrains. As an example, the retrofit diesel-electric hybrid delivery trucks purchased by FedEx were projected to improve fuel economy by 44% compared to standard diesel delivery trucks.⁷⁰ Fleet expectations for fuel savings from diesel-electric hybrid urban buses were typically 35-45%⁷¹ and expectations for fuel savings from diesel-electric hybrid school buses were similar (improvement from 7 to 11 mpg was projected from the Eaton hybrid added to the Trigg County, Kentucky fleet).⁷² These expectations were based upon information provided by consultants and equipment sales personnel.

Improvements to commercial truck fuel economy can translate into significant reductions in annual fuel consumption, as discussed in Section 2.2.2. Because baseline fuel economy for all trucks averages just 6.5 mpg, annual fuel consumption can be comparatively high even for vehicles with limited annual mileage. For instance, the first 235 hybrid buses to operate in the Seattle area were expected to save 750,000 gallons of fuel per year over the buses they replaced: over a 12-year life cycle, this would equate to savings of about 8 million gallons of fuel. GM has estimated that if America's nine largest cities replaced their transit fleets with hybrids, the 40 million gallon fuel savings from those 13,000 buses would be greater than 500,000 passenger vehicles.⁷³

Actual Experience

Fleet fuel economy experience with diesel-electric hybrid delivery vehicles has been varied. Some hybrid truck fleets have been able to achieve the expected improvements in fuel economy, while others have fallen well short of expectations. While improvements of up to 40% may be possible, the actual improvement for some fleets has been 5% or less, depending upon driver behavior and route.⁷⁴

⁷⁰ Bird, Alison. (July, 2009). FedEx Converts 92 Delivery Trucks to Hybrids, Expanding Hybrid-Electric Fleet by 50%, *Green Car Congress*. Retrieved from <http://www.greencarcongress.com/2009/07/fedex-converts-20090721.html> .

⁷¹ Wald, M.L. (December 25, 2004). "Magic" Fuel-Saving Buses Fall a Bit Short on Wonders, The New York Times. Retrieved from <http://www.energybulletin.net/node/3789> .

⁷² Kentucky Clean Fuels Coalition. (March, 2011). Hybrid Electric School Bus Takes to the Road in Trigg County. Retrieved from <http://www.kentuckycleanfuels.org/resources/hybridhorsepower-trigg.htm> .

⁷³ Meredith, Mike. (2004). First GM Hybrid Transit Buses Go To Work, *MSN Autos*. Retrieved from <http://editorial.autos.msn.com/article.aspx?cp-documentid=435202>

⁷⁴ Interview. (September, 2011) Vice President of Global Vehicles, FedEx.

Coca-Cola Enterprises' experience with their beverage hauler tractors has been that fuel economy has improved anywhere from 12 – 35%, from 5 - 6 mpg for a diesel to 6 - 7.5 mpg for a diesel-electric hybrid. Achievement of 30% is possible but requires careful matching of trucks to the right duty cycle. Geography is also important as optimal results are not achieved on hills and grades.⁷⁵

Greater real world improvements to fuel economy have been achieved by diesel-electric hybrid buses running routes in congested cities. The BAE HybriDrive system has been evaluated across a variety of bus duty cycles. Fuel economy improvement is greatest for "stop and go" cycles with average speeds between 5 – 20 mph: in these duty cycles, actual improvement may be as great as 46%, at the high end of expectations.⁷⁶

Table 12: BAE HybriDrive Fuel Economy Improvement Under Various Duty Cycles

	Manhattan	TFL	HTUF	OCTA	CILCC	FTP72 (FUDS)
F/E % Improvement	46%	33%	37%	36%	23%	25%
Average Speed (kph)	10.9	13.9	15.9	19.5	22.1	31.1
Stops/Min	1.1	1.2	0.4	1.0	0.5	0.7

Source: Dr. Mike Mekiche. (October, 2011). HybriDrive Parallel Propulsion System, *HTUF National Conference*

Although actual urban bus experience has included improvements of fuel economy that achieve highest expectations in some applications, fuel economy gains have fallen short in many other applications:

- Connecticut Transit, a state bus agency, is running two 40-foot buses with the GM hybrid powertrain. According to Stephen W. Warren, the assistant general manager for maintenance, "We were slightly disappointed with the fuel economy," which he said was 10 percent to 15 percent better than new buses of conventional design.
- New Jersey Transit purchased seven hybrid buses anticipating fuel savings of 20 - 40 percent. Spokeswoman Penny Bassett Hackett has indicated that savings have been at the lower end of the range.

⁷⁵ Interview. (December, 2011). Director of Fleet Operations – North America, Coca-Cola Refreshments.

⁷⁶. Retrieved from <http://www.kentuckycleanfuels.org/resources/hybridhorsepower-trigg.htm> .

- Southeast Pennsylvania Transportation Authority, located in the Philadelphia area, is not tracking the fuel economy of its GM hybrid buses, but the assistant general manager of operations has declared that "We're not getting worse mileage, but if somebody's justifying the cost differential based on fuel savings, it's a stretch."
- King County Metro Transit estimates that its fleet of hybrid buses will save Seattle less than half the fuel claimed.⁷⁷

In bucket truck applications, expectations for improved fuel economy have generally been met or exceeded. Significant fuel efficiencies are possible in this application because the diesel engine can be turned off for battery enabled vehicles while performing maintenance work with the aerial boom. Reductions to fuel consumption of 1,000 to 1,500 gallons annually per vehicle have been estimated by the Hybrid Truck Users Forum, while Cox Communications estimates that the 15 hybrids in its New England fleet have each achieved fuel savings of more than 2,200 gallons annually.⁷⁸

Reasons for Fuel Economy Shortfalls

Actual fuel economy improvements have differed from expectations for a variety of reasons including the impact of route selection upon performance of hybrid vehicle diesel emissions systems, driver behavior, and significant improvements to baseline diesel fuel economy.

- **Impact of Route Selection upon Diesel Hybrid Emissions Systems**

Burning off trapped diesel exhaust particulates in the 2010+ emissions systems requires a regeneration event where the exhaust must reach and maintain a certain temperature. Although this temperature is typically met during the daily operation of a conventional diesel vehicle, the engine-off periods in a hybrid can interrupt this cycle. Delivery fleets have found that regeneration may not occur unless the truck's route includes 10-12 miles of freeway driving. In that case, periodic manual regeneration needs to be performed on the hybrid trucks, requiring up to 30 minutes of engine operation at high rpm.

In Los Angeles, Staples found that the engine control module in one vehicle had called for regeneration 119 times but the engine only ran long enough to

⁷⁷ Wald, M.L. (December 25, 2004). "Magic" Fuel-Saving Buses Fall a Bit Short on Wonders, The New York Times. Retrieved from <http://www.energybulletin.net/node/3789>.

⁷⁸ Nesi, Ted. (November, 2008). Cox, Verizon Add Hybrids to Vehicle Fleets, Providence Business News. Retrieved from <http://www.pbn.com/Cox-Verizon-add-hybrids-to-vehicle-fleets,36408>.

complete the process three times. The incomplete regeneration required the driver to pull to the side of the road to complete a manual regeneration process.⁷⁹ While this is an extreme case, other trucks also required periodic manual particulate trap regeneration. Fuel consumption during required manual regeneration cycles can actually place diesel-electric hybrids at a fuel economy disadvantage compared to conventional diesel powertrains.⁸⁰

- **Driver Characteristics**

Actual fuel economy improvements achieved with hybrid trucks may be very driver dependent. Routes and associated vehicles for some fleets may be assigned on the basis of seniority. The right driver on the right route can provide a 40% improvement to fuel economy, while the wrong driver on that route might yield only a 10% improvement.⁸¹

- **Improvements to Baseline Diesel Fuel Economy**

Some fleets believe that improvements to conventional diesel engines have significantly closed the gap to diesel-electric hybrid fuel economy. Whereas hybrid fuel economy of around 6.5 mpg might have been 40% better than a baseline diesel for a Class 4 walk-in delivery van in 2002, the hybrid improvement relative to new diesel trucks is now smaller.⁸²

Some of the tools for fuel economy optimization can provide significant efficiency to conventional diesel vehicles, substantially narrowing the potential fuel economy advantage of diesel-electric hybrids. In 2006, Staples achieved a 25% improvement in its conventional diesel fleet (to 10.1 mpg from 8.1 mpg) by installing speed governors to limit the top speed of all vehicles to 60 mph. Analysis by Staples found that extra time on the road was more than offset by less time refueling. These \$7 modules, in combination with electronic idle reduction and driver training, have enabled Staples to improve fleet overall fuel economy by 30% without significant capital cost.⁸³ Coca-Cola Enterprises has trained 11,000 of its drivers in “Ecodriving” skills, such as how to accelerate smoothly, coast more, select proper gears and use the topography to significantly benefit fuel economy.⁸⁴

⁷⁹ Lyden, Sean. (March, 2011). What Staples Expects from All-Electric Medium-Duty Work Trucks, Work Truck. Retrieved from <http://www.worktruckonline.com/Channel/Green-Fleet/Article/Story/2011/03/What-Staples-Expects-from-All-Electric-Medium-Duty-Work-Trucks/Page/3.aspx>

⁸⁰ Interview. (September, 2011). Director of Vehicle Engineering, UPS.

⁸¹ Ibid.

⁸² Interview. (September, 2011) Vice President of Global Vehicles, FedEx.

⁸³ U.S. Department of Energy. (April, 2011). Staples and Massachusetts Clean Cities Deliver on Fuel Efficiency., Hybrid Electric Fleet Experiences. Retrieved from http://www.afdc.energy.gov/afdc/progs/fleet_exp_fuel.php?HEV .

⁸⁴ Interview. (December, 2011). Director of Fleet Operations – North America, Coca-Cola Refreshments.

Diesel-electric hybrid powertrains regained some of their fuel economy advantage over conventional diesel powertrains with the implementation of 2010 diesel emissions standards. These standards are estimated by UPS to have decreased conventional diesel fuel economy by 5 - 6%, even after improvements due to advanced exhaust gas recirculation (EGR).⁸⁵

⁸⁵ Interview. (September, 2011). Director of Vehicle Engineering, UPS.

5.4 Maintenance and Reliability Experience

At purchase, fleet managers generally anticipated that maintenance of diesel-electric hybrid vehicles would be lower than for conventional vehicles, with the possible exception of the battery and hybrid specific components. It was expected that regenerative braking would reduce stresses and strains upon the drivetrain and brake systems. In transit bus service, it was anticipated that intervals between brake linings could be increased to 70,000 miles, engine oil drain intervals could be increased to 24,000 miles from 6,000 miles, and engines would last the life of the bus.⁸⁶ King County Metro Transit expected to save 32,000 gallons of oil per year through reduced oil changes.⁸⁷

Maintenance of diesel hybrid vehicles has overall been less than required for the conventional diesel powertrains that they replaced. However, savings in delivery vehicle applications have not been as great as the 25% some consultants had projected. Delivery vehicles retrofitted with hybrid powertrains had particular issues with body and suspension parts not modified as part of the conversion. Fleet managers believe, however, that the lack of dramatic reductions to maintenance expense might be related to the challenging, short route stop-and-go duty cycles selected for the vehicles.⁸⁸

In bus service, improvement to maintenance and reliability was more dramatic. Whereas diesel vehicles went about 3,100 miles between trouble calls (unanticipated events taking the bus out of service), diesel-electric hybrid buses placed in service in 2004 went 6,400 miles between service calls, while more complex vehicles purchased in 2010 went 4,000 – 4,300 miles. Engine and brake wear have been reduced. Although specific maintenance reduction data is unavailable,⁸⁹ lower maintenance requirements enabled King County Metro Transit to reduce staff by 24 mechanics (about 10 percent).⁹⁰

⁸⁶ K. Chandler and K. Walkowicz. (December, 2006). King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results, National Renewable Energy Laboratory. Retrieved from <http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/40585.pdf>.

⁸⁷ Meredith, Mike. (2004). First GM Hybrid Transit Buses Go To Work, MSN Autos. Retrieved from <http://editorial.autos.msn.com/article.aspx?cp-documentid=435202>

⁸⁸ Interview. (September, 2011) Vice President of Global Vehicles, FedEx.

⁸⁹ Interview. (September, 2011). Vehicle Maintenance Manager, King County Metro Transit.

⁹⁰ Pence, Karly. (Fall, 2006) Hybrid Buses Fuse More Than Electricity, Gasoline, ej magazine.

Retrieved from <http://news.jrn.msu.edu/ejmagazine/2011/05/03/hybrid-buses-fuse-more-than-electricity-gasoline/>.

Battery durability has been better than anticipated across all duty cycles. One fleet manager remarked of delivery applications that there were “no issues,”⁹¹ although other fleets are withholding judgment until longer time-in-service data has been acquired. Bus fleet expectation at the time of purchase decisions was that batteries would last only 4-5 years in service but, according to King County Metro Transit, “after 7 years we’ve only replaced a handful.”⁹²

⁹¹ Interview. (September, 2011) Vice President of Global Vehicles, FedEx.

⁹² Interview. (September, 2011). Vehicle Maintenance Manager, King County Metro Transit.

5.5 Fleet Environmental Goals

Corporate objectives for hybrid fleets usually include corporate responsibility as a key element. The Coca-Cola Enterprises hybrid electric fleet, for instance, fulfills a component of its Corporate Responsibility and Sustainability program aiming to reduce emissions by 30%, improve fuel economy by 30% and reduce noise pollution. According to the Vice President of Indirect Procurement, "Fleet operations is an integral part of our Corporate Responsibility and Sustainability commitment at Coca-Cola Enterprises, particularly in our CRS focus area of energy conservation/climate change."⁹³

Diesel-electric hybrids are anticipated to significantly reduce emission of pollutants. The reduction of pollutants in delivery service compared to a conventional diesel truck is estimated by FedEx at about 96% for particulates and 75% for NOx.⁹⁴ The reduction in urban bus applications is estimated by King County Metro Transit at 90% for particulates and 50% for NOx.⁹⁵ At New York City Transit, particulates dropped by 97% and NOx by 58%.⁹⁶

Improved fuel economy also translates into reduced CO₂ emissions: the leverage of a given percentage improvement to fuel economy for a medium truck is about 3-times that of a passenger car, while the leverage for a heavy truck is about 30-times that of a passenger car.⁹⁷ For delivery vehicles, UPS estimated that a single one-time purchase of 130 diesel-hybrids reduce CO₂ emissions by 671 tons of CO₂ annually (about 5 tons per vehicle), equivalent to removing 128 passenger cars from the road. For bucket trucks, the reductions to annual greenhouse gas emissions are estimated at 11.0 to 16.5 tons per vehicle according to the Hybrid Truck Users Forum.⁹⁸

⁹³ Shelly Mika. (July 2009). Coca-Cola Enterprises Invests Big in Hybrid Trucks. Retrieved from <http://www.worktruckonline.com/Article/Print/Story/2009/07/Coca-Cola-Enterprises-Invests-Big-in-Hybrid-Trucks.aspx>

⁹⁴ Alison Bird. (July, 2009). FedEx Converts 92 Delivery Trucks to Hybrids, Expanding Hybrid-Electric Fleet by 50%, *Green Car Congress*. Retrieved from <http://www.greencarcongress.com/2009/07/fedex-converts-20090721.html> .

⁹⁵ Mike Meredith. (2004). First GM Hybrid Transit Buses Go To Work, *MSN Autos*. Retrieved from <http://editorial.autos.msn.com/article.aspx?cp-documentid=435202>

⁹⁶ Micheline Maynard. (October 20, 2009). As Hybrid Buses Get Cheaper, Cities Fill Their Fleets, *The New York Times*. Retrieved from <http://www.nytimes.com/2009/10/22/automobiles/autospecial2/22BUS.html> .

⁹⁷ Marcy Lowe, Gloria Ayee and Gary Gereffi. (2009). Hybrid Drivetrains for Medium- and Heavy Duty Trucks, *Manufacturing Climate Solutions*. Center on Globalization Governance & Competitiveness. Retrieved from

http://www.cggc.duke.edu/environment/climatesolutions/greeneconomy_Ch9_HybridDrivetrainsforTrucks.pdf.

⁹⁸ Shelley Mika. (August, 2007). UPS Trademark Brown Delivery Trucks Go Green, *Work Truck Online*. Retrieved from <http://www.worktruckonline.com/Article/Story/2011/winders>

Cox Communications indicates that, given their better than anticipated fuel savings from diesel-electric hybrids, actual reductions to CO₂ emissions have been closer to 31 tons per vehicle.⁹⁹

Reduced noise levels during electric function are an additional benefit of hybrid vehicles, both to passengers and passers-by. Reduced noise combined with reduced emissions can be of particular importance during tunnel operation, as for the King County Metro Transit buses that drive in electrified “Hush” mode through the tunnel under downtown Seattle which has limited ventilation over its mile plus length.¹⁰⁰

[01/UPS-Trademark-Brown-Delivery-Trucks-Go-Green.aspx?interstitial=1](http://www.pbn.com/01/UPS-Trademark-Brown-Delivery-Trucks-Go-Green.aspx?interstitial=1)

⁹⁹ Ted Nesi. (November, 2008). Cox, Verizon Add Hybrids to Vehicle Fleets, *Providence Business News*. Retrieved from <http://www.pbn.com/01/UPS-Trademark-Brown-Delivery-Trucks-Go-Green.aspx?interstitial=1>.

¹⁰⁰ Interview. (September, 2011). Vehicle Maintenance Manager, King County Metro Transit.

5.6 Driver Acceptance and Training

Driver Acceptance

Driver acceptance of diesel-electric vehicles has been high: drivers usually like driving hybrid vehicles. They find that the vehicles are easy to drive, offer equivalent or better performance, and may be less fatiguing. Getting greatest benefit from hybrids requires that drivers understand how the vehicles' operation differs from diesel or gas vehicles and how to best operate the new vehicles.

Capital Area Transit Authority in Lansing, Michigan, said that they had described operation of diesel-electric hybrid buses to their drivers as comparable to driving an electric golf cart. Bus drivers have generally been pleased with the performance of the hybrid buses, including faster acceleration and regenerative braking. A prior fleet maintenance manager at King County Metro Transit, believes that there is also less operator fatigue with dynamic braking: "We have one phase of the dynamics braking built into the throttle pedal so when drivers lift their foot off the throttle, it will actually slow the bus without having to depress the brake pedal."¹⁰¹

Driver Training

Driver training is provided in how to best optimize fuel economy by delivery fleets such as Coca-Cola Enterprises and UPS as well as by powertrain manufacturers such as BAE and Eaton. Driver training may include appropriate launch of the vehicle, maximization of brake regeneration, how to accomplish passive regeneration of the particulate trap and other tips. Training can help manage important differences between diesel-electric hybrid and conventional diesel characteristics: in the case of buses, one unanticipated training need was to help drivers manage the comparatively high rate of acceleration possible with a hybrid.¹⁰²

Fleets complement training with various tools to manage driver behavior in pursuit of fuel economy improvement. Onboard telematics are almost universally installed to provide capability to track vehicle usage. Monetary incentives are also being employed by some fleets. UPS has found that driver education in environmental impact has been a more powerful motivator to behavioral change than emphasis upon fuel economy.¹⁰³

¹⁰¹ Karly Pence. (Fall, 2006) Hybrid Buses Fuse More Than Electricity, Gasoline, ej magazine. Retrieved from <http://news.jrn.msu.edu/ejmagine/2011/05/03/hybrid-buses-fuse-more-than-electricity-gasoline/>.

¹⁰² Interview. (September, 2011). Vehicle Maintenance Manager, King County Metro Transit.

¹⁰³ Ibid.

Hybrid truck manufacturers have also recognized the importance of driver feedback to maximize hybrid vehicle fuel efficiency. Freightliner and Hino Trucks now provide gauges and displays in their hybrid truck models to provide feedback on things such as battery state-of-charge, and coach the driver to operate the vehicle in the most efficient manner.

Service Training

Hybrid powertrain manufacturers such as BAE Systems and Eaton provide service training to commercial fleet customers for their hybrid systems. Although diesel hybrids may have generally improved reliability compared to conventional diesel vehicles, their maintenance procedures are specialized. Hybrid drivetrain systems, regenerative braking systems, and high voltage electronics require unique service training. Since manufacturers may require a certain number of technicians to conduct a training program, some fleets such as Coca-Cola Enterprises have been required to restrict their hybrid vehicles to large cities, avoiding smaller towns.

5.7 Incentives and Other Financial Considerations

A hybrid-electric truck or bus normally carries a substantial price premium over its conventional engine counterpart. As a result, most fleet purchases of diesel-electric hybrids have been made with the help of Federal or State funding. Companies such as UPS have been careful to strategically utilize these funding sources to offset cost penalties for diesel-electric hybrids compared to conventional diesel powertrains.¹⁰⁴

Federal Incentives

The Federal Alternative Motor Vehicle Credit, enacted by the Energy Policy Act of 2005, provided tax credits for Heavy Hybrid trucks and buses, as described in Section 2.2.1 Federal and State Government Purchase Incentives. These credits expired in 2010, and the only remaining Federal tax incentive is for plug-in hybrid and electric vehicles up to 14,000 lb. GVW.¹⁰⁵

The American Recovery and Reinvestment Act (ARRA) made additional funding available to support purchase of diesel-electric hybrid trucks through the Environmental Protection Agency's Diesel Emission Reduction Act (DERA). Funding was provided for up to 25% of the cost of a new hybrid truck and fleets were able to purchase multiple trucks; an existing diesel truck had to be taken out of service for each new hybrid truck purchased.¹⁰⁶ Other ARRA funding was provided for hybrid fleet purchases, and the U.S. Department of Energy has provided funding through its Clean Cities program.

Fleets have taken advantage of these Federal "stimulus" programs as a major source of funding for diesel hybrid vehicles:

- The King County Metro Transit purchase of 170 Orion buses in 2011 was made with the help of a \$35.8 million grant from the ARRA.¹⁰⁷ The \$210,600 per vehicle grant offset the differential between the typical diesel-electric hybrid bus

¹⁰⁴ Interview. (September, 2011). Director of Vehicle Engineering, UPS.

¹⁰⁵ Bill Van Amburg. (October, 2011). The Fight for Funding, HTUF National Conference. Retrieved from http://calstart.org/Files/Presentations/HTUF_2011/Fight-for-Funding-Bill-Van-Amburg-CALSTART.pdf.

¹⁰⁶ Unknown. (March, 2009). Eaton Assists Heavy Truck Fleet Owners in Applying for Government Diesel Hybrid Grant, Work Truck Magazine. Retrieved from <http://www.worktruckonline.com/News/Story/2009/03/Eaton-Assists-Truck-Fleet-Owners-in-Applying-for-Government-Diesel-Hybrid-Grants.aspx?interstitial=1>

¹⁰⁷ King County Department of Transportation. (May, 2011). Press Release: New Clean, Green Hybrid Buses Hit the Streets Today. Retrieved from http://www.kingcounty.gov/transportation/kcdot/NewsCenter/NewsReleases/2011/May/nr052311_hybride_xpansion.aspx

priced at about \$500,000 and its conventional diesel counterpart priced at about \$300,000.

- Lubbock Transit Authority in Texas funded the entire purchase price of three hybrid buses with \$1.6 million from ARRA.
- Clermont Transportation Connection in Ohio will use part of its \$1.4 million ARRA grant to buy four hybrid buses.
- Intercity Transit of Olympia, Washington ordered six hybrids, partly funded by \$2.3 million in ARRA funds. The marketing and communications manager stated, "We would not be purchasing at this time if it wasn't for the stimulus money."
- Chicago Transit Authority announced it was purchasing 58 articulated hybrid buses for \$49 million, using some of its \$241 million of stimulus funds.¹⁰⁸
- Washington Metropolitan Transit Authority was allocated \$202 million from ARRA, including purchase of 48 new diesel-electric hybrid buses."¹⁰⁹

Other Federal programs have also been sources of funding for diesel-electric hybrid vehicles:

- Kentucky Department of Education was awarded \$13 million by the U.S. Department of Energy in August, 2009 to cover the incremental costs of hybrid buses and build the nation's largest fleet of hybrid school buses.¹¹⁰
- UPS ordered 130 diesel-electric hybrid Freightliner delivery trucks. Deployment was funded in part by grants from the U.S. Department of Energy's Clean Cities program.

Major fleets in many instances have obtained funding with the assistance of powertrain manufacturers. For instance, Eaton established programs to assist diesel truck fleet owners in applying for the \$156 million in grants for diesel hybrid trucks made available under the American Recovery and Reinvestment Act (ARRA).¹¹¹ Specialized consulting firms have also built practices from matching customers to Federal programs. GNA is a consulting firm with offices in Santa Monica and San Diego, California, Phoenix and New

¹⁰⁸ Joseph Pisani. (April, 2009). Stimulus Package Driving Hybrid Bus Orders, CNBC. Retrieved from http://www.cnbc.com/id/30194631/Stimulus_Package_Driving_Hybrid_Bus_Orders

¹⁰⁹ Washington Metropolitan Area Transit Authority. (September, 2010). Press Release: Metro Showcases New Vehicles, Bus Body and Paint Shop Funded by Federal Recovery Act Dollars,. Retrieved from http://www.wmata.com/about_metro/news/PressReleaseDetail.cfm?ReleaseID=4645

¹¹⁰ Whayne Power Systems. (July, 2010). Press Release: The First Hybrid School Bus to Hit the Road in LaRue County. Retrieved from <http://www.whayne.com/PowerSystems/Documents/hybrid%20bus%20news%20release.pdf>

¹¹¹ Unknown. (March, 2009). Eaton Assists Heavy Truck Fleet Owners in Applying for Government Diesel Hybrid Grant, Work Truck Magazine. Retrieved from <http://www.worktruckonline.com/News/Story/2009/03/Eaton-Assists-Truck-Fleet-Owners-in-Applying-for-Government-Diesel-Hybrid-Grants.aspx?interstitial=1>

York that has secured more than \$210 million in grants over the past 20 years, including 20% of the \$300 million awarded under the Clean Cities solicitation.¹¹²

Federal incentives have been substantially reduced with the non-renewal of the “stimulus” programs and the 2010 expiration of the Federal Alternative Motor Vehicle Credit for Heavy Hybrids.

State Incentives

As discussed in Section 2.2.1 Federal and State Government Purchase Incentives, the California Air Resources Board (ARB) created the Hybrid Truck and Bus Voucher Project (HVIP) to speed introduction of hybrid trucks and buses purchased and operated in California. The intent of the California program is to offset about half the incremental cost of a hybrid truck.¹¹³ The HVIP incentive amounts for 2011 are shown in the table below.

Table 13: California Incentives for Hybrid Truck/Bus Purchases in 2011

Gross Vehicle Weight in Pounds (lbs)	Base Incentive¹
8,501 – 10,000 lbs ²	Plug-in Hybrid Zero-Emission
	\$10,000
	\$15,000
10,001 – 19,500 lbs	\$15,000 ³
19,501 – 33,000 lbs	\$20,000
33,001 – 38,000 lbs	\$25,000
> 38,000 lbs	\$30,000

¹The first HVIP-eligible vehicle purchased by a fleet and ARB-certified hybrid vehicles above 14,000 lbs are each eligible for an additional \$5,000 voucher.
²This weight category includes plug-in hybrid and zero-emission vehicles only.
³Zero-emission commercial vehicles in this weight category are eligible for \$20,000

Source: Hybrid Truck and Bus Voucher Incentive Project, California Air Resources Board

Other states have various programs to incentivize hybrid truck purchases, however these are generally targeted or pursued in association with chosen corporate partners. The Maryland Energy Administration (MEA) partnered with Maryland Clean Cities and the high profile fleets of ARAMARK, Efficiency Enterprises, Nestlé Waters North America, Sysco Corporation, and United Parcel Service. Known as the Maryland Hybrid

¹¹² Gladstein, Neandross & Associates. (October, 2010). Press Release: UPS Expands Its Alternative Fuel Vehicle Fleet with New Order for 130 Hybrid Electric Delivery Trucks. Retrieved from <http://www.automotive-fleet.com/Article/Print/Story/2010/12/GREEN-FLEET-Green-Initiatives-Surge-in-Commercial-Truck-Fleets.aspx>

¹¹³ Hybrid Truck and Bus Voucher Incentive Project. (Unknown). Making the Case for Hybrid and Electric Trucks and Buses. Retrieved from http://www.californiahvip.org/article_MakingTheCase.asp

Truck Initiative (MHTI), this project utilized \$5.9 million in grant funding to help offset the incremental cost to purchase and deploy 143 Freightliner hybrid electric vehicles and Freightliner Custom Chassis hydraulic hybrid vehicles for local goods movement fleets.¹¹⁴

Other Financial Considerations

Incorporation of diesel hybrid vehicles into fleets may have the effect of increasing the operating costs of the remaining conventional diesel vehicles. Fleet managers may find that incorporation of diesel hybrids requires that they restructure their vehicle leases. In a typical fleet, the fleet manager may move vehicles from route to route to equalize mileage within the lease mileage limitations and control cost per mile. Allocation of short routes to hybrids or battery electric vehicles removes these short routes from the fleet, so that remaining vehicles may hit their maximum mileage in a shorter period of time (e.g., five years instead of seven).

¹¹⁴ Maryland Hybrid Truck Initiative. (Unknown). Website Home Page. Retrieved from <http://www.marylandhti.com/>

5.8 Fleet Business Case

Many fleet managers are willing to consider hybrid-electric drivetrain technology ahead of other alternative fuels to green their fleets, but purchase cost for hybrids remains the top inhibitor. These were outcomes of a CALSTART Hybrid and E-Truck market survey of fleet managers completed in 2011. This study also determined that one-third of respondents expect it to take 5-6 years to recover the incremental cost of a hybrid truck, while roughly another third expect it to take less time and the remaining third expect it to take more time, as shown in the figure below.¹¹⁵

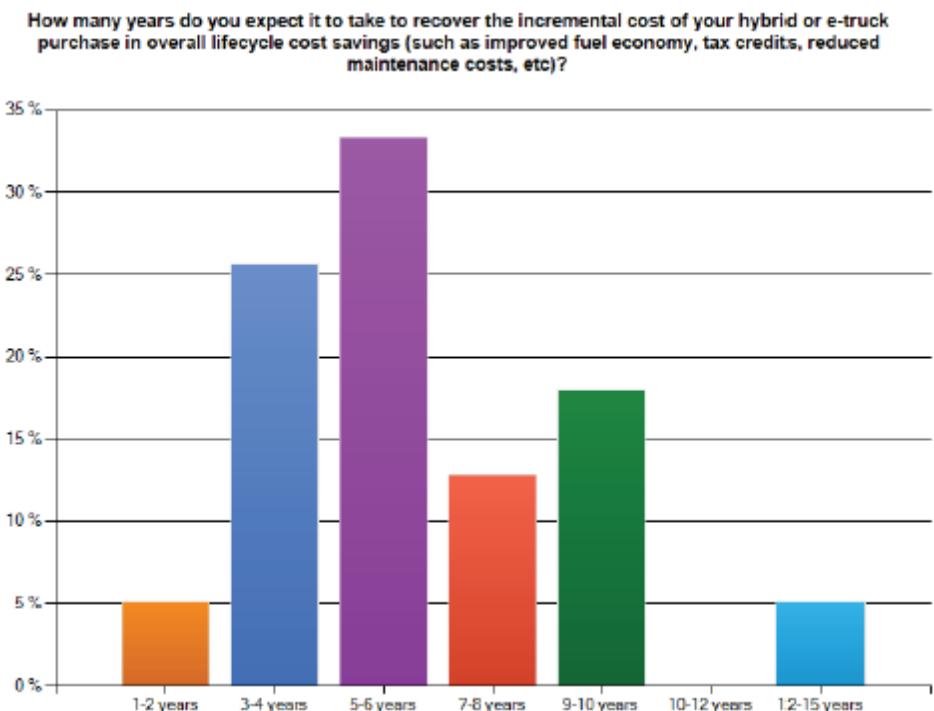


Figure 65: Expected Investment Recovery Period for Hybrid Trucks

Source: Pitkanen, Hubert. (October, 2011). Market Demand Survey: Hybrid Trucks and E-Trucks, HTUF National Conference. Retrieved from http://calstart.org/Files/Presentations/HTUF_2011/Market-Assessment-Whitney-Pitkanen-CALSTART.pdf .

A positive business case is believed by fleet managers to exist for bus hybrid applications. This business case is built upon incentives, projected savings in fuel costs

¹¹⁵ Pitkanen, Hubert. (October, 2011). Market Demand Survey: Hybrid Trucks and E-Trucks, HTUF National Conference. Retrieved from http://calstart.org/Files/Presentations/HTUF_2011/Market-Assessment-Whitney-Pitkanen-CALSTART.pdf .

and reduced maintenance expense to offset purchase penalties. Incentives are probably the most important part of the equation, sometimes amounting to the entire purchase price. For example, New Jersey Transit¹¹⁶ paid for the extra cost of its hybrid buses with a Federal grant meant to stimulate new technologies, and Lubbock Transit Authority in Texas funded the entire purchase price of three hybrids with \$1.6 million from ARRA.¹¹⁷ Fuel savings are the second largest component, but for most bus fleets lifetime fuel savings will offset less than one-half the purchase premium for a hybrid vehicle.

Although the stop-and-go duty cycle of urban delivery applications may be near optimal for hybrid operation, delivery vehicles typically do not accumulate enough mileage for fuel economy benefits to translate into financially compelling fuel savings. The National Renewable Energy Laboratory found in a study of UPS hybrid-electric delivery vans that they have achieved fuel economy gains of 29 to 37 percent.¹¹⁸ However, delivery applications still require significant reductions in battery cost to establish a viable business equation. As one executive remarked, “Payback of nine or ten or more years is the same as never.”¹¹⁹

UPS looks for a return on investment within three to five years for all of the alternative powertrain trucks they purchase.¹²⁰ UPS estimates that achieving a 3-year payback to the hybrid price premium at present diesel fuel prices will require a 50% decrease in battery prices, in combination with a real world 30% fuel economy benefit.¹²¹ FedEx estimates that an overall 70% reduction to operating costs would be required to justify a 60% price premium of a hybrid compared to a conventional diesel vehicle.¹²² Coca-Cola Enterprises believes that \$5 diesel fuel prices are required to make diesel-electric hybrid vehicles financially viable.¹²³

The fuel savings for plug-in hybrid bucket trucks can average up to 60%, or significantly more than the 30 – 40% seen in typical hybrid delivery trucks. The hybrid bucket trucks can avoid extensive engine idle time by using the hybrid system batteries to provide power for on-board equipment or exportable power at a jobsite. However, these plug-in hybrid vehicles often carry two battery packs to provide this additional power,

¹¹⁶ Wald, M.L. (December 25, 2004). “Magic” Fuel-Saving Buses Fall a Bit Short on Wonders, The New York Times. Retrieved from <http://www.energybulletin.net/node/3789>.

¹¹⁷ Pisani, Joseph. (April, 2009). Stimulus Package Driving Hybrid Bus Orders, CNBC. Retrieved from http://www.cnbc.com/id/30194631/Stimulus_Package_Driving_Hybrid_Bus_Orders

¹¹⁸ Hybrid Truck and Bus Voucher Incentive Project. (Unknown). Making the Case for Hybrid and Electric Trucks and Buses. Retrieved from http://www.californiahvip.org/article_MakingTheCase.asp

¹¹⁹ Interview. (September, 2011). Vice President of Global Vehicles, FedEx.

¹²⁰ Hance, Michael, UPS. (October 11, 2011) Remarks at HTUF National Conference.

¹²¹ Interview. (September, 2011). Director of Vehicle Engineering, UPS.

¹²² Interview. (September, 2011). Vice President of Global Vehicles, FedEx.

¹²³ Interview. (December, 2011). Director of Fleet Operations – North America, Coca-Cola Refreshments.

meaning that the fuel savings may be still be insufficient to offset the higher battery costs.¹²⁴

The business case for hybrid vehicles appears to be under increasing pressure. Besides non-renewal of the various Federal tax credits and stimulus programs that initially stimulated demand, the fuel economy of conventional diesel engines has been improving due to advances in diesel powertrain technology, fuel economy optimization hardware (e.g., speed governors and idle reduction), and driver training.

¹²⁴ Interview. (September 2011). Program Manager, Verizon Fleet Sustainability.

5.9 Future Product Wants

In a recent CALSTART market assessment, fleet managers were asked what their desired technological innovations were for future hybrid and electric trucks. The most common responses included:¹²⁵

- Improved battery lifespan / technology - reduced battery costs
- Improved performance in winter conditions and off-road driving
- Lower weight of technology with increased range
- Faster charge time and improved infrastructure at remote sites
- Electric Power Take-off (EPTO) over a full hybridized driveline

Among 65 survey respondents, 35 fleets indicated that they were considering the purchase of a total of 12,000 hybrid and battery electric vehicles over the next five years. These fleets represented “early adopters,” as the majority already operated some number of MD and HD hybrid vehicles.¹²⁶ Although the total sales might be higher as other fleets purchase hybrids for the first time, this remains a very small annual volume within the context of the overall U.S. medium/heavy truck market, forecast at 340,500 trucks for 2012.¹²⁷

Fleet operators identified the critical factors that would induce them to invest further in hybrid and battery electric vehicles in this survey. The top four factors identified were predominantly economic: improved performance, high fuel prices, subsidies or tax breaks, reduced maintenance costs, as indicated in the figure below.

¹²⁵ Pitkanen, Hubert. (October, 2011). Market Demand Survey: Hybrid Trucks and E-Trucks, HTUF National Conference. Retrieved from http://calstart.org/Files/Presentations/HTUF_2011/Market-Assessment-Whitney-Pitkanen-CALSTART.pdf .

¹²⁶ Ibid.

¹²⁷ Kilcarr, Sean. (January, 2012). DTNA Forecasts Strong Truck Sales for 2012, Fleet Owner. Retrieved from <http://fleetowner.com/equipment/news/dtna-forecasts-strong-truck-sales-0112/> .

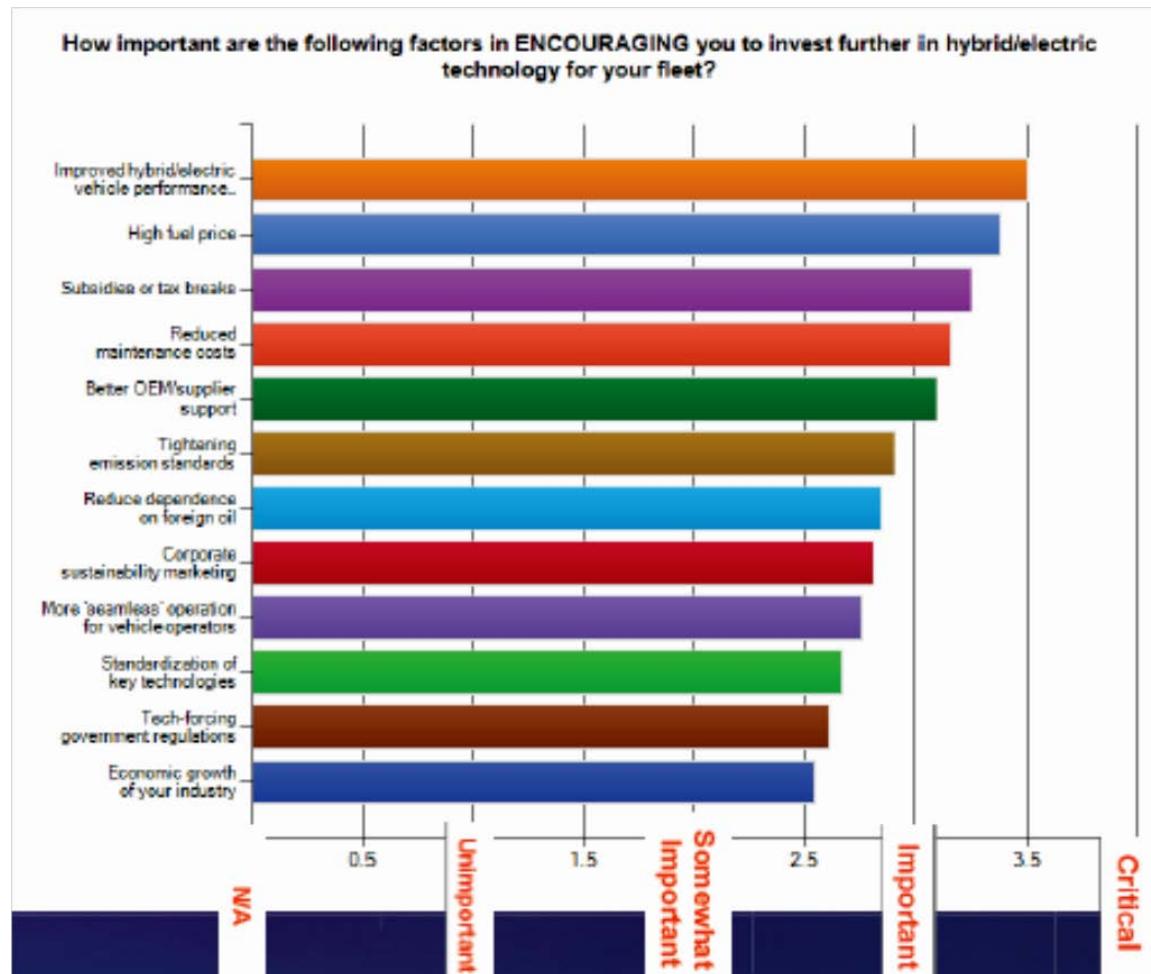


Figure 66: Fleet Owner Views on Most Important Factors for Purchase of Additional HEVs/EVs

Source: Hubert Pitkanen. (October, 2011). Market Demand Survey: Hybrid Trucks and E-Trucks, HTUF National Conference.

Delivery Vehicles

Initial focus of technology evolution for delivery vehicles was on basic features and robustness. This was because early vehicles did not have such basic features as air conditioning and were plagued by body, steering and suspension issues relating to overlay of the electric powertrain and battery upon the existing diesel powered chassis.

Moving forward, delivery fleet interest is for a hybrid delivery vehicle with an optimized powertrain. Current hybrid delivery vans also do not take full advantage of

opportunities for improved fuel economy because the hybrid powertrain is sometimes utilized with the same size diesel engine as the conventional powertrain. The majority of the FedEx and UPS hybrid delivery vans employ the large 6.0L diesel engines that are installed standard to their vehicles, while also carrying the added weight of an electric powertrain and battery. Some fleet managers interviewed believe that a series (rather than parallel) hybrid configuration using a diesel powertrain of smaller displacement (e.g., 4.0L) and electric drivetrain with larger traction motor and battery size would provide opportunity for significant improvements to operating costs and perhaps establish a viable business equation.

Staples has been testing a bolt-on, post-transmission hybrid system on its Isuzu delivery trucks. The Fleet Equipment Manager for Staples believes that in an optimized hybrid, the electric launch system should be paired to a smaller diesel engine sized to maintain vehicle speed and return 25-30 mpg or more. "For instance, if an Isuzu truck runs a 5.4L four-cylinder diesel with a bolt-on hybrid system used to electrically launch the vehicle, once that vehicle gets up to speed, it still has a 210-hp, 5.4L diesel when all that is needed is about 130 horses to maintain the truck's speed." According to him, Isuzu acknowledges a 210-hp engine is not needed with a properly integrated hybrid system, however Isuzu does not currently offer a smaller diesel engine certified to meet U.S. emissions standards.¹²⁸

Fleet operator belief is that low current sales volumes and manufacturer focus upon emissions compliance do not support development of diesel-electric hybrids optimized for delivery fleets.¹²⁹ However, current vehicles are considered too expensive to be economically viable because of insufficient volumes of production, especially around batteries. As one fleet executive put it, "There are not enough do-gooders out there to create economies of scale."¹³⁰

FedEx believes that diesel-electric hybrids are only a bridging strategy to some other drive technology. In the opinion of the FedEx VP of Global Vehicles, "the hybrid has run its course."¹³¹

¹²⁸ Ibid.

¹²⁹ Interview. (September, 2011). Vice President of Global Vehicles, FedEx.

¹³⁰ Interview. (September, 2011). Program Manager, Verizon Fleet Sustainability.

¹³¹ Interview. (September, 2011). Vice President of Global Vehicles, FedEx.

Many delivery truck fleets are now purchasing or evaluating battery electric vehicles (BEVs) in addition to diesel hybrids.

- Frito-Lay is deploying 176 electric trucks, which it estimates will save half a million gallons of fuel annually.¹³²
- FedEx ordered 40 electric trucks to add to its current fleet of 45, and is currently negotiating an additional order. FedEx expects that its electric fleet will double by the end of the year.¹³³
- Staples added 41 new all-electric Class 6 Smith Newton delivery trucks to its North America fleet in 2011.¹³⁴
- Coca-Cola Enterprises purchased six eStar Navistar battery electric vehicles¹³⁵
- AT&T purchased two Ford Transit Connect electric vans and began using a Smith Newton cargo truck in its St. Louis fleet.¹³⁶
- UPS is also piloting battery electric vehicles.¹³⁷

When selecting BEVs, fleets need to be conscious of annual replacement needs and the fact that trucks often get redeployed to new routes when older ones are turned in. As Mike Payette of Staples notes, "Specializing your fleet to where 20 percent of trucks operate on electricity limits you to routes less than 70 miles a day, so you have to be very selective in how you specify your fleet."¹³⁸

¹³² Katers, Nick. (September, 2010). Frito-Lay North America Purchasing 176 All-Electric Trucks from Smith Electric Vehicles. Retrieved from <http://www.hybridmile.com/news/frito-lay-north-america-purchasing-176-all-electric-trucks-from-smith-electric-vehicles/>

¹³³ Interview. (September, 2011) Dennis Beal, Vice President of Global Vehicles, FedEx.

¹³⁴ Lyden, Sean. (March, 2011). What Staples Expects from All-Electric Medium-Duty Work Trucks, Work Truck. Retrieved from <http://www.worktruckonline.com/Channel/Green-Fleet/Article/Story/2011/03/What-Staples-Expects-from-All-Electric-Medium-Duty-Work-Trucks/Page/3.aspx>

¹³⁵ Coca-Cola Company. (September, 2011). Press Release: Coca-Cola Leads the Charge Toward Greener Fleets. Retrieved from http://www.thecocacolacompany.com/dynamic/press_center/2011/09/leading-the-charge-toward-greener-fleets.html

¹³⁶ Staff. (December, 2010). Green Initiatives Surge in Commercial Truck Fleets, Green Fleet. Retrieved from <http://www.greenvetmagazine.com/article/2664/green-initiatives-surge-in-commercial-truck-fleets/p/3>

¹³⁷ Staff. (December 2010). UPS Purchases 130 Hybrids & Pilots All-Electric Vans, Automotive Fleet. Retrieved from <http://www.automotive-fleet.com/Article/Print/Story/2010/12/GREEN-FLEET-Green-Initiatives-Surge-in-Commercial-Truck-Fleets.aspx>

¹³⁸ Simon, Chad. (March, 2011). Staples Fleet Tests Diesel-Electric Viability, Business Fleet. Retrieved from <http://www.businessfleet.com/Article/Print/Story/2010/03/Staples-Fleet-Tests-Diesel-Electric-Viability.aspx>

Examples of battery electric delivery vehicles in fleets include the FedEx Navistar eStar and Frito-Lay Smith Newton EV as shown in the figure below.



Figure 67: FedEx Navistar eStar and Frito-Lay Smith Newton Electric Vehicles

Source: Staff. (March 2011). Green Initiatives Surge in Commercial Truck Fleets, *Green Fleet Magazine*.

In the view of Staples, battery electric vehicles are ideal for urban markets such as Los Angeles, as well as other inner city/metropolitan markets. Staples has 180 routes which are between 35-70 miles per day, within the “sweet spot” of the battery electric vehicle operating range. Volumes are limited, however, by the marginal business case—payback in the delivery vehicle duty cycle at 2011 diesel fuel costs (roughly \$3.40 to \$4.10 per gallon¹³⁹) is estimated at 10 years, excluding maintenance savings.¹⁴⁰

Urban Buses

Bus fleets will likely increase adoption of diesel hybrids. The economic drivers are improved fuel economy, increased reliability (miles between trouble calls) and reduced maintenance. However, reduced Federal incentives may slow the pace of adoption.

The King County Metro Transit plan is to go 100% hybrid. In addition, government grants are being creatively applied to investigate potential fuel economy improvements from technologies that reduce engine loads and instead leverage available electrical power. Field trials are being conducted on a smart thermal management system from

¹³⁹ U.S. Energy Information Administration. (January 2012). Gasoline and Diesel Fuel Update. Retrieved from <http://www.eia.gov/petroleum/gasdiesel/>.

¹⁴⁰ Lyden, Sean. (March, 2011). What Staples Expects from All-Electric Medium-Duty Work Trucks, *Work Truck*. Retrieved from <http://www.worktruckonline.com/Channel/Green-Fleet/Article/Story/2011/03/What-Staples-Expects-from-All-Electric-Medium-Duty-Work-Trucks/Page/3.aspx>

Engineered Machined Products (so called “mini-hybrid” technology), as shown in the figure below, along with electric-assist steering.



Figure 68: Smart Thermal Management – Engineered Machined Products

Source: MiniHybrid Thermal Kit, Engineered Machined Products Website

Full electric operation of buses is also being investigated using Seattle’s legacy overhead cable system to provide power and battery charging (only five such cable systems remain in the U.S.).¹⁴¹

Bucket Trucks

Bucket trucks have seen early introductions of plug-in hybrid (PHEV) systems, which allow the truck to operate on-board equipment at a job site without running the engine. However, some PHEV trucks require two battery packs which results in higher battery cost. The key desire of bucket truck fleets is reduced battery cost to establish a positive business case to go with the superior functional characteristics of diesel-electric hybrids (e.g., exportable power, stable aerial platform). Some fleets indicate that battery electric bucket trucks would be considered at the right economics.¹⁴²

¹⁴¹ Interview. (September, 2011). Vehicle Maintenance Manager, King County Metro Transit.

¹⁴² Interview. (September 2011). Program Manager, Verizon Fleet Sustainability.

5.10 Enablers to Adoption

CALSTART has identified three enablers to speeding fleet adoption of diesel-electric hybrid trucks:

1. Develop government policy framework that will ensure strong, consistent long-term funding and incentives: 50% identified as “minimum threshold level for effective incentive.”
2. Focus subsidies on research and development directed to lowering the purchase price premium.
3. Develop battery leasing programs to reduce vehicle purchase price.¹⁴³

Federal and state incentives were discussed in prior sections and the importance of offsetting the purchase price premium of hybrid and battery electric vehicles has been well established as a key element of accomplishing acceptable business cases. Navistar has experimented with sales incentives including rebates, vehicle leases and battery leases.¹⁴⁴ Fleets such as Coca-Cola Enterprises express interest in these incentives as a possible tool to improve their business cases.¹⁴⁵

¹⁴³ Pitkanen, Hubert. (October, 2011). Market Demand Survey: Hybrid Trucks and E-Trucks, HTUF National Conference. Retrieved from http://calstart.org/Files/Presentations/HTUF_2011/Market-Assessment-Whitney-Pitkanen-CALSTART.pdf.

¹⁴⁴ Unknown. (August, 2008). Industry-First Hybrid Battery Lease, Other Incentives Power Navistar’s Diesel Hybrid Leadership, *Work Truck Magazine*. Retrieved from <http://www.worktruckonline.com/News/Story/2008/08/GM-and-Navistar-Allow-Medium-Duty-Truck-MOU-to-ExpireIndustry-First-Hybrid-Battery-Lease-Other-Inc.aspx?interstitial=1> .

¹⁴⁵ Interview. (December, 2011). Director of Fleet Operations – North America, Coca-Cola Refreshments.

6.0 Competing Alternatives to Diesel-Electric Hybrid Powertrains

It is important to acknowledge the progress being made in other powertrain technologies for MD and HD trucks and buses that may compete with diesel-electric hybrids as customers attempt to save on fuel costs. While not the primary focus of this study, two competing technologies are Hydraulic Hybrid drivetrains and engines fueled on natural gas. Progress is also being made on fuel cell auxiliary power units that could lessen the demand for hybrid powertrains that are also used to provide standby power, such as in over-the-road Class 8 semi-tractors.

6.1 Hydraulic Hybrid Drivetrains

A key objective in a hybrid powertrain vehicle is to recapture the vehicle's kinetic energy during deceleration, store it in some other form, and then use it to help accelerate the vehicle to save energy at the primary power source. An electric hybrid does this by generating electricity which is stored in a battery, while a hydraulic hybrid uses a pressurized hydraulic fluid storage system to capture and deploy energy. Despite recent reductions, battery cost remains a significant barrier to wide-spread adoption of hybrid-electric powertrains. Hydraulic hybrids (sometimes called Hydraulic Launch Assist, or HLA) are a viable alternative that are coming to market in certain types of trucks with duty cycles that match the particular capabilities of this system.

Electric and Hydraulic Hybrids Compared

- In a charge-sustaining electric hybrid, electric power is continually stored over a long period of time in a battery (dark blue) and accessed only as needed during peak power demands or for electric-only propulsion (light blue). This system has high energy density but lower power density.

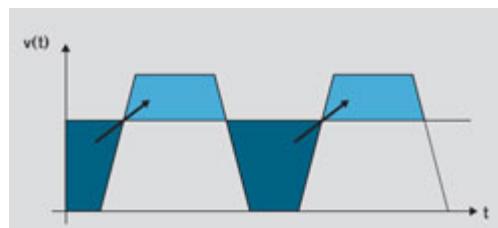


Figure 69: Electric Hybrid Energy Storage and Use

- In a hydraulic hybrid, kinetic energy is captured during braking and transferred to a hydraulic accumulator (dark blue) and immediately used when accelerating again (light blue). This system has high power density but lower energy density. It can store a large amount of kinetic energy in a short time, but immediately gives it all back during acceleration. As a result, a hydraulic hybrid system is best suited for heavy vehicles that have frequent start-stop cycles, such as refuse trucks, delivery trucks, and transit buses.

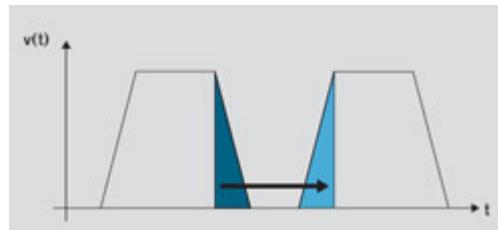


Figure 70: Hydraulic Hybrid Energy Storage and Use

- A key advantage of a hydraulic hybrid over an electric is that it can return to the drive wheels a much greater percentage of kinetic energy recaptured under braking. Freightliner has published data showing that in a Class 6 delivery truck braking from 35 – 0 mph at 0.1 g deceleration, a hydraulic hybrid can return 71% of the recaptured kinetic energy to the wheels while the electric hybrid returns just 21%.¹⁴⁶

Like the electric hybrid system, there are also parallel and series hydraulic hybrid configurations.

- A **parallel hydraulic hybrid** retains the direct connection between the engine/transmission and the drive wheels, and adds a hydraulic pump/motor connected directly to the transmission or driveshaft. This allows the hydraulic system to assist the gasoline engine during acceleration and recapture energy during deceleration, but it does not allow the engine to shut off when the vehicle is stopped.
- A **series hydraulic hybrid** vehicle has no direct connection between the engine and drive wheels. It utilizes one hydraulic pump/motor connected to the engine, and a second hydraulic pump/motor (or wheel motors) to provide driving torque. The engine can be shut off when the vehicle is at rest, which means a

¹⁴⁶ Bryant, Dave, Freightliner Trucks. (Sep. 19, 2011). Hybrid/Electric/Alt Fuel Update. Technology & Maintenance Council 2011 Fall Meeting

series HHV has the potential for greater fuel economy improvement than a parallel.

- Parallel or blended systems are being used primarily in Class 4/5/6 trucks, while series systems are being used mostly in Class 7/8 trucks.¹⁴⁷

The range of hydraulic hybrid system designs is contrasted in the figure below.

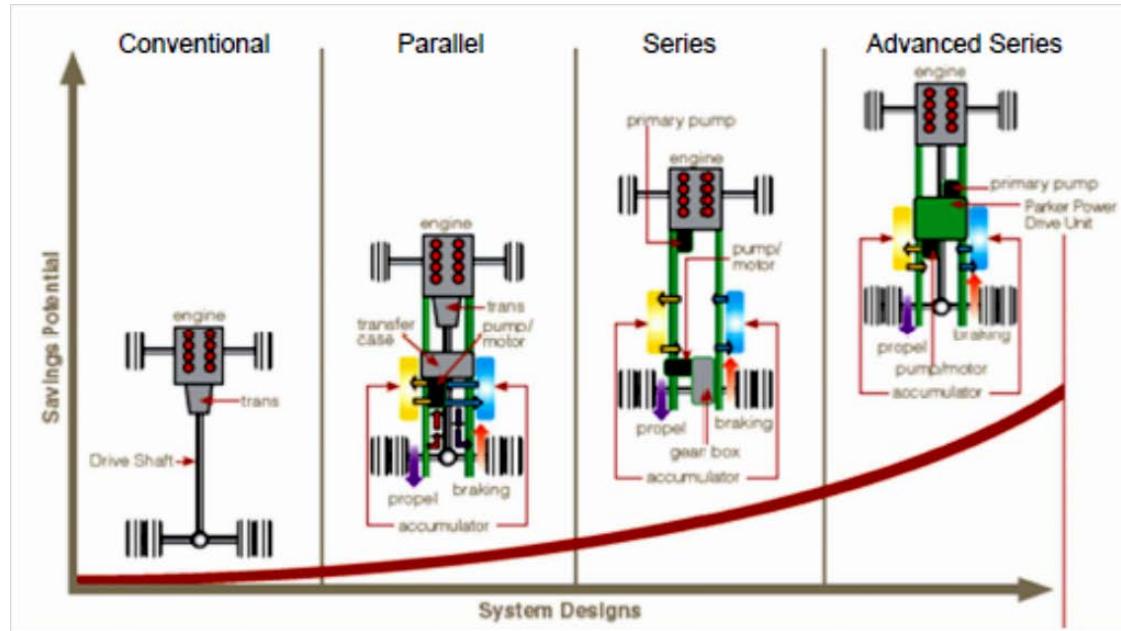


Figure 71: Hydraulic Hybrid System Architectures

Source: Bryant, Dave, Freightliner Trucks. (Sep. 19, 2011). Hybrid/Electric/Alt Fuel Update. Technology & Maintenance Council 2011 Fall Meeting

Hydraulic hybrid systems have package space, weight, and noise concerns that make them best suited for medium- and heavy-duty truck applications.

- The systems require significant in-vehicle package space to accommodate the low and high pressure fluid accumulators. The pump/motor must also be packaged concentric to the driveshaft in a parallel hybrid, or two pump/motors accommodated for a series hybrid.

¹⁴⁷ Bryant, Dave, Freightliner Trucks. (Sep. 19, 2011). Hybrid/Electric/Alt Fuel Update. Technology & Maintenance Council 2011 Fall Meeting

- These components plus the hydraulic fluid add significant weight to a vehicle. Bosch Rexroth quotes 500 kg (~1100 lb) for their commercial refuse truck system that produces 250 kW power.
- The system also produces hydraulic pump noise when in operation. This may not be an issue in a refuse truck that already has hydraulic rams and lifts producing noise.

Hydraulic hybrid drivetrain systems are being manufactured by several companies, the most prominent of which are Bosch, Parker Hannifin and Eaton Corporation. There are a growing number of trucks on the market using these systems. One example is the Peterbilt Model 320 Hybrid truck with a Cummins ISL diesel engine and Eaton Hydraulic Launch Assist (HLA) system that is aimed at refuse hauler applications. In testing, this truck demonstrated up to a 30% improvement in fuel economy, 30 to 40% reduction in emissions, and over 50% reduction in brake wear.¹⁴⁸ Two driver-selectable driving modes are offered in this vehicle. In “fuel economy mode,” stored energy is used to launch the vehicle and then the engine comes on to add power for higher speeds and cruising. In “performance mode,” the engine is on at launch and the stored energy is released and blended with engine power during acceleration. In the latter case, a double-digit savings in fuel economy can still be realized, along with an 18% improvement in acceleration.¹⁴⁹

¹⁴⁸ Peterbilt website. Retrieved from <http://www.peterbilt.com/hybrid320.1.aspx>

¹⁴⁹ Peterbilt Press Release. (March 24, 2010). Peterbilt Launches Model 320 Hybrid. Retrieved from <http://www.peterbilt.com/newsdetails.aspx?id=285>

6.2 Natural Gas Fueled Engines

Natural gas vehicles are growing in popularity, particularly in the medium- to heavy-duty vehicles market. Natural gas is now widely used in transit buses, school buses, refuse trucks, package delivery trucks, and vehicles used in ports. One thing these all have in common is that they can be refueled at a central location. This is not the case with light-duty vehicles that travel where natural gas might be difficult to find. Companies like Clean Energy have successfully driven natural gas vehicle use by building fueling stations and supplying natural gas under multi-year contracts to fleets at costs significantly less than the per-gallon cost of gasoline or diesel.¹⁵⁰

The fuel can be supplied either as compressed natural gas (CNG) or liquefied natural gas (LNG). CNG is typically stored in steel or composite containers at high pressure (3000 to 4000 psi). These containers are not typically temperature controlled, but are allowed to stay at local ambient temperature. LNG is stored at pressures close to atmospheric, but at temperatures as low as -260°F (-162°C) which requires vacuum insulated storage tanks. At these temperature and pressure conditions, natural gas is in a liquid state and is far denser than even the highly compressed state of CNG.¹⁵¹

LNG heavy-duty trucks are eligible for Federal tax credits in the United States and may be eligible for other state-specific emissions credits. Natural gas trucks generally provide superior return on investment to hybrid-electrics, but need additional investment in infrastructure and new truck engines.¹⁵²

One of the principal drivers for natural gas as a vehicle fuel has been the increasing price differential between natural gas and both diesel fuel and gasoline, which have increased by 50 – 60% over the past 2-1/2 years while LNG and CNG prices have remained fairly constant. Diesel fuel now costs nearly twice as much as LNG on a gallon equivalent basis, as illustrated in the figure below.

¹⁵⁰ NaturalGasVehicles.com website. Retrieved January 24, 2012 from <http://naturalgasvehicles.com/>

¹⁵¹ Wikipedia, Natural Gas Vehicle. Retrieved January 24, 2012 from http://en.wikipedia.org/wiki/Natural_gas_vehicle

¹⁵² Bryant, Dave, Freightliner Trucks. (Sep. 19, 2011). Hybrid/Electric/Alt Fuel Update. Technology & Maintenance Council 2011 Fall Meeting

Average Monthly Fuel and Crude Prices

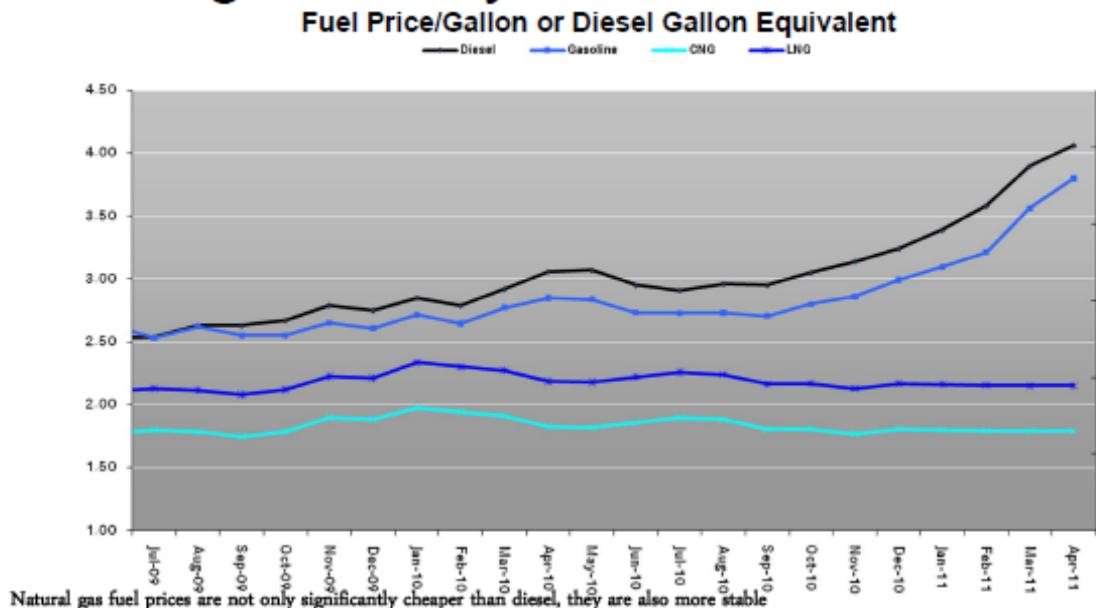


Figure 72: Natural Gas Price Compared to Gasoline and Diesel Fuel: 2009-2011

Source: Bryant, Dave, Freightliner Trucks. (Sep. 19, 2011). Hybrid/Electric/Alt Fuel Update. Technology & Maintenance Council 2011 Fall Meeting

The principle benefits for natural gas vs. diesel as a truck fuel are as follows:¹⁵³

- Improving operating economics vs. diesel
- Increasing diesel fuel costs driving quick NG payback
- Reduced after-treatment complexities
- Reduced GHG emissions (up to 23%)
- Noise reduction of 5-12 dba vs. diesel
- Domestic Fuel/Energy Security
- Renewable Fuel

Key challenges for natural gas are:

- Lack of Refueling Infrastructure
- Fuel Tank Cost, Packaging, and Weight
- Wide Range of New NG Engines Needed for Truck Applications
- Maintenance Facility Upgrades

¹⁵³ Ibid.

The primary issue with natural gas as a fuel for trucks and buses is the lack of refueling infrastructure. At present there are about 800 natural gas stations available nationwide, compared to 175,000 stations dispensing gasoline. Centrally fueled fleets have the advantage of vehicles returning to a common location where a natural gas refueling station can be installed. This has made natural gas attractive for transit buses, and there were nearly twice as many NG-fueled transit buses in service in 2010 as there were hybrid-electric buses. Pike Research forecasts that this gap will close rapidly, and that both bus powertrain types will grow on a comparable pace through 2016, as shown in the figure below.

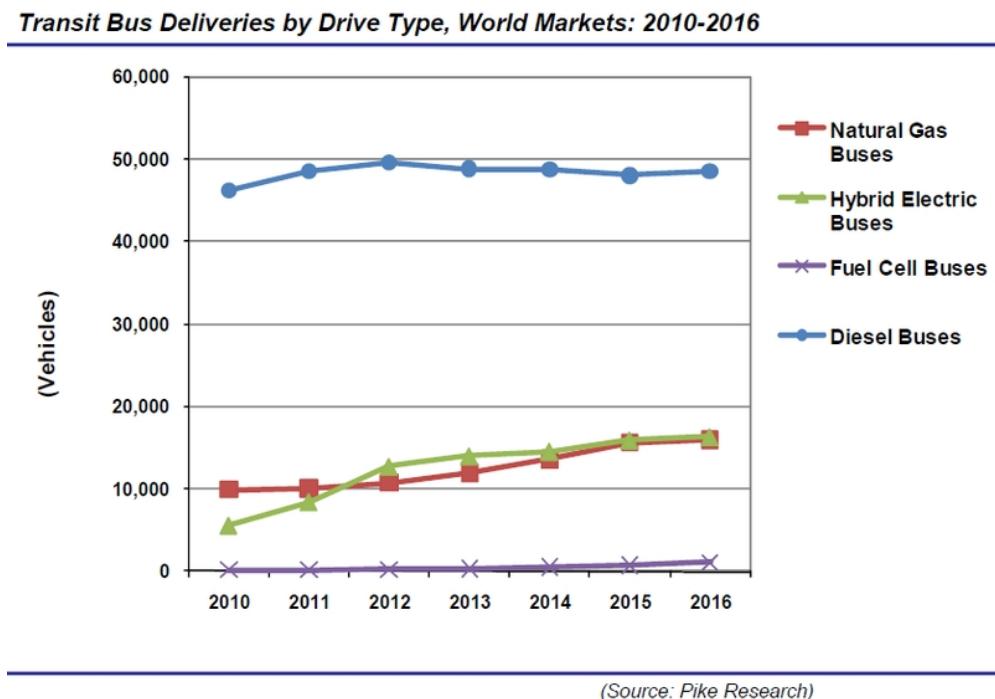


Figure 73: Forecast of Transit Bus Deliveries by Powertrain Type: 2010-2016

Source: Pike Research

Investments are now being made in building up an LNG refueling infrastructure across the U.S. that will service over-the-road trucks. Clean Energy Fuels Corp., the leading provider of natural gas fuel for transportation in North America, unveiled a route plan in January, 2012 for the first phase of 150 new LNG fueling stations for America's Natural Gas Highway (ANGH). The company has identified 98 locations and anticipates having 70 stations open by the end of 2012 in 33 states, and the remaining 80 stations open by the end of 2013. Many of the fueling stations will be co-located at Pilot-Flying J Travel

Centers already serving goods movement trucking. Pilot will build, own and operate natural gas fueling facilities at agreed-upon travel centers.¹⁵⁴

The 150 first-phase ANGH stations coincide with the expected arrival of new natural gas truck engines well suited for heavy-duty, over-the-road trucking. Engine manufacturers and original equipment truck manufacturers such as Cummins-Westport, Kenworth, Peterbilt, Navistar, Freightliner and Caterpillar are expected to have Class-8 trucks available in engine sizes allowing for varied road and driving requirements

This LNG refueling route plan is shown in the figure below.

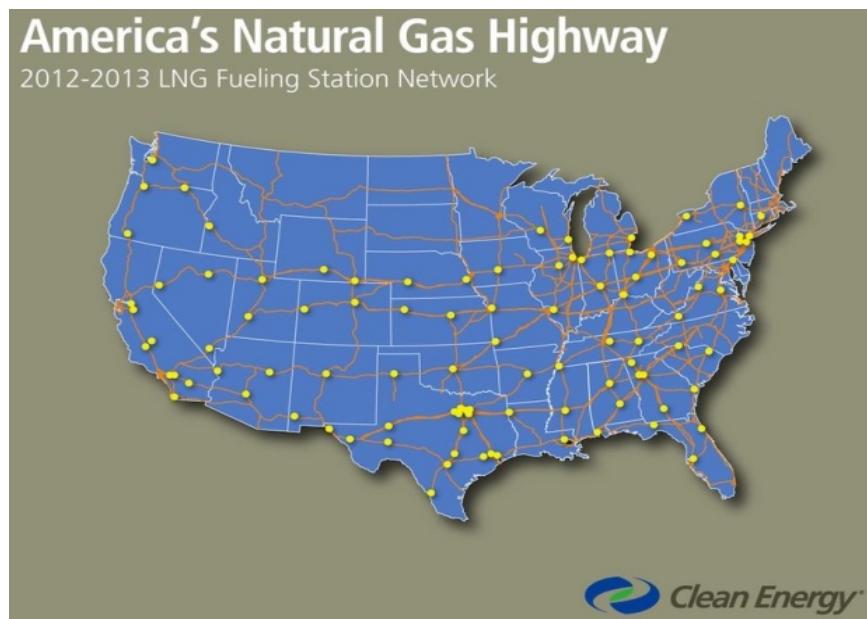


Figure 74: Clean Energy Fuels Corp. 2012-2013 LNG Fueling Station Network

Source: Green Car Congress. (January 12, 2012). Clean Energy unveils LNG backbone network for America's Natural Gas Highway; 150 LNG stations by end of 2013.

¹⁵⁴ Green Car Congress. (January 12, 2012). Clean Energy unveils LNG backbone network for America's Natural Gas Highway; 150 LNG stations by end of 2013.

Commercial LNG/CNG Vehicles

Daimler Trucks North America (DTNA) announced the delivery of its 1,000th natural gas truck in November, 2011, and is the first commercial vehicle manufacturer to achieve such a milestone.

- The Freightliner 114SD CNG truck is powered by a Cummins Westport ISL G 8.9 liter engine, the only one of its kind that is a factory-produced, dedicated natural gas engine. It was delivered to customer Ryder System, Inc.
- DTNA leads the automotive manufacturing market in the production of natural gas powered conventional commercial vehicles with a combined sales figure of 3,600 natural gas vehicles across its Daimler Trucks North America brands, including Thomas Built Buses and Freightliner Custom Chassis.

Peterbilt has also partnered with Westport Innovations and Cummins Engines to provide a variety of natural gas-fueled trucks. Peterbilt's Model 386 truck is available with Westport's GX LNG engine, while their Models 384, 365 and 367 are offered with factory installed Cummins ISL-G engines using LNG. Peterbilt also offers the Model 320 with a CNG power platform, which excels in refuse applications.

- The Westport LNG fuel system is comprised of LNG fuel tanks, proprietary Westport fuel injectors, cryogenic fuel pumps and associated electronic components to facilitate robust performance and reliable operation.
- This LNG version of the engine offers the same horsepower, torque, and efficiency as the base diesel engine.



Figure 75: Westport LNG Fuel System Used by Peterbilt

Source: Peterbilt website. Retrieved January 23, 2012 from <http://www.peterbilt.com/eco/Design-LNG.htm>

6.3 Fuel Cell Auxiliary Power Units

Delphi Corporation is working to develop and test fuel cell technology for truck auxiliary power units to satisfy increasingly stringent anti-idling legislation and other proposals addressing commercial truck emissions, noise and fuel consumption. If fuel cell power units can be brought to market at a reasonable cost, they may become attractive for certain truck applications that might otherwise look to hybrid-electric systems to generate on-board or exportable power.

Delphi's Solid Oxide Fuel Cell (SOFC) converts chemical energy in conventional fuels directly into useful electrical power without combustion. When used as a heavy-duty truck auxiliary power unit (APU), the Delphi SOFC operates independently from the truck's internal combustion engine to produce up to 5 kW of power to run in-cab electrical accessories such as cab lights, refrigerators, and audio systems. Currently, operators power those features by idling their main engines or with diesel engine APUs. According to development testing, Delphi's SOFC APU can reduce fuel consumption during idling by up to 85 percent.¹⁵⁵

In future applications, Delphi's goal is to have the SOFC APU provide power to replace belt-driven components such as engine cooling fans and water pumps. This will remove loads from the primary engine, resulting in improved vehicle fuel economy and engine performance.

Testing of the Delphi SOFC system is underway by several truck manufacturers including Peterbilt on their Model 386 tractor truck. The SOFC installation on this vehicle is shown in the figure below.



Figure 76: Delphi Solid Oxide Fuel Cell Power Unit on Peterbilt 386 Truck

Source: Peterbilt website. Retrieved January 23, 2012 from <http://www.peterbilt.com/eco/Design-FuelCell.htm>

¹⁵⁵ Delphi website. Retrieved from <http://delphi.com/manufacturers/auto/fuelcells/>

7.0 Hybrid Electric Truck and Bus Manufacturer Summary

7.1 OEMs producing hybrid trucks and buses

The following vehicle manufacturers are engaged in the development and manufacture of diesel-electric medium- and heavy-duty hybrid trucks and buses for the North American market.

Hybrid Truck Manufacturers

- Azure Dynamics Corp. (with Ford Motor Co.)
- Crane Carrier Company
- Daimler Trucks NA
 - Freightliner Trucks
 - Freightliner Custom Chassis
- Hino Motors
- Mack Trucks (Volvo Group)
- Navistar International Corporation
 - IC Bus and Engine Corporation
 - Workhorse Custom Chassis
- Oshkosh Truck Corporation
- PACCAR Inc.
 - Kenworth Truck Company
 - Peterbilt

Hybrid Bus Manufacturers

- Alexander Dennis Limited (ADL)
- Azure Dynamics Corp. (with Ford Motor Co.)
- Daimler Trucks NA
 - Orion Bus
 - Thomas Built Buses
- DesignLine Corporation

- Ebus
- El Dorado-National
- Gillig
- ISE Corporation
- Iveco/Volgren
- MAN
- MCI
- Motor Coach Industries
- NABI
- New Flyer Industries
- North American Bus Industries
- Nova Bus
- Optare
- Solaris
- SOR
- VDL Bus and Coach
- Volvo Buses
- Wrightbus

7.2 System and component suppliers

Hybrid Systems

Hybrid-Electric Drive Systems and Conversions (Truck & Bus)

- Allison Transmission (GM)
- Azure Dynamics
- BAE Systems
- Cummins Crosspoint
- Eaton Corp.
- Enova Systems
- ISE Corporation
- Meritor
- Siemens VDO

Plug-in HEV Conversions

- ALTe
- Azure Dynamics
- Electric Vehicles International
- Enova Systems
- Odyne/Dueco
- Rapid Electric Vehicle (REV)
- Terex

Integrated Starter Generator (ISG) and Belt Alternator Starter (BAS) Systems

- Continental
- Delphi
- Denso
- Robert Bosch
- Valeo

Energy Storage

Batteries

- A123 Systems
- Advanced Battery Technologies Inc.
- Altairnano
- Automotive Energy Supply Company (AESC)
- Axeon Technologies Ltd
- batScap, a division of the Bolloré Group
- BYD
- Cobasys
- Dow Kokam
- ENER1/EnerDel
- Energy Conversion Devices/Ovonics
- Exide
- Hitachi
- Johnson Controls (JCI)
- LG Chem Power Inc.
- Optima
- Primearth EV Energy Co (Panasonic EV)
- Saft Groupe SA
- Sanyo Electric
- SK Energy
- Valence Technology

Ultracapacitors

- Aowei Technology Development Company
- batScap, a division of the Bolloré Group
- EnerDel
- Graphene Energy
- Ioxus, Inc..
- LS Mtron
- Maxwell Technologies Inc.
- Nesscap Co. Ltd
- Nippon Chemi-Con

Hybrid Drive Components

Power Electronics – Inverters, Converters, Controllers

- AC Propulsion
- Aerovironment
- Continental AG
- Delphi Electronics
- Denso Corp.
- Dueco Inc.
- Eaton Corp.
- Energy CS
- Enova Systems
- Hitachi Ltd.
- Kollmorgen
- Phoenix Drives
- Robert Bosch
- Siemens VDO
- TDK
- UQM Technologies Inc. (formerly Unique Mobility)
- US Hybrid
- Valeo SA

Drive Motors

- Bosch Rexroth
- Enova Systems
- Hitachi Ltd.
- Remy International
- Robert Bosch
- Siemens VDO
- TM4, Inc.
- Toshiba Corp.
- UQM Technologies Inc. (formerly Unique Mobility)
- US Hybrid
- Valeo S.A.
- Variable Torque Motors
- WaveCrest

In-Wheel and Other Motor Systems

- BAE Systems
- Magna E-Car Systems
- Protean Electric
- ZF Friedrichshafen AG

Transmissions for HEVs

- Aisin Seiki Co. Ltd.
- Allison Transmission, Inc.
- Eaton Corporation
- Fallbrook Technologies, Inc.
- Freescale Semiconductor, Inc.
- Meritor

7.3 Aligned Industry Groups

There are a number of organizations that have been working over the last decade or so to advance the development of diesel-electric hybrid vehicle technology and help bring commercially viable vehicles to market. These organizations and their involvement are detailed below.

Hybrid Truck Users Forum (HTUF) - Formed by the Army's TARDEC in partnership with CALSTART in order to speed the development of hybrid powertrain technology for trucks and buses and promote fleet trials and acceptance. It has done this through technology exchanges and national forums that bring together manufacturers, decision makers and fleet customers. This has led to trials of the first medium- and heavy-duty hybrid trucks in utility fleets and urban delivery service, and is viewed to have accelerated the development of new hybrid truck technologies by 18 – 24 months.

CALSTART - Works with business, fleets, and government to develop and implement clean, efficient transportation solutions. Achieves this by focusing on four key activities that together provide the unique combination to support a growing industry:

- Clean Transportation Industry Services: Providing value-add services to companies: timely information, partnering, new business opportunities, conferences, technology evaluation
- Clean Transportation Solutions Group – Consulting: Helping ports, property developers, transit districts, and fleets seeking to implement cost-effective, customized solutions
- Policy: Advancing key policies, advising policymakers, and helping companies plan for the future
- Technology Commercialization: Identifying opportunities, building teams, securing funding, and advancing technology, vehicles, fuels, and systems

CALSTART also administers HTUF, and has recently opened the CalHEAT (Hybrid Efficient & Advanced Truck) Research Center that is operating with California Energy Commission funding and involves a broad partner team. The goal of CalHEAT is to accelerate the commercialization of technologies which reduce petroleum use, greenhouse gases and air pollution and help meet California goals for carbon and petroleum reduction.

Electric Drive Transportation Association (EDTA) - US industry association dedicated to the promotion of electric drive as the best means to achieve the highly efficient and clean use of secure energy in the transportation sector. EDTA conducts public policy advocacy, education, industry networking, and international conferences. Since 1989, has supported the sustainable commercialization of all electric drive transportation technologies by providing in-depth information, education, industry networking, public policy advocacy and international conferences and exhibitions. As a unified voice for the electric drive industry, EDTA membership includes a diverse representation of vehicle and equipment manufacturers, energy providers, component suppliers, and end users.

SAE International - A global association of more than 128,000 engineers and related technical experts in the aerospace, automotive and commercial vehicle industries. SAE develops standards governing all vehicle technical areas including commercial trucks and hybrid-electric vehicle propulsion system design. It also hosts conferences and symposiums that gather industry experts to discuss and disseminate new technology developments in commercial trucks and hybrid propulsion.

National Truck Equipment Association (NTEA) - Represents nearly 1,600 companies that manufacture, distribute, install, sell and repair commercial trucks, truck bodies, truck equipment, trailers and accessories. Buyers of work trucks and the major commercial truck chassis manufacturers also belong to the Association. NTEA provides in-depth technical information, education, and member programs and services, and produces The Work Truck Show.

8.0 Implications for the U.S. Military

Synopsis

One of the U.S. military's highest priorities is increasing the fuel efficiency of its ground vehicle fleet. The development of commercial hybrid truck and bus powertrain technology is expected to help improve the fuel efficiency of tactical vehicles as well through technology transfer. A variety of MD and HD hybrid trucks and buses are now listed on the 2012 GSA Vehicle Schedule, with trucks including chassis-cabs, dump, stake bed, refrigerated, tractors, and cargo vans. This will help the non-tactical fleets on U.S. bases meet the various Executive Orders and Performance Plans which require efficiency improvement and partial electrification.

The Department of Defense (DOD) also has significant initiatives underway to establish the feasibility of operating micro-grids on bases, supplied by renewable energy sources and utilizing plug-in hybrid and full electric vehicles to provide two-way power flow in a Vehicle-to-Grid (V2G) system. The recent introduction and further development of medium- and heavy-duty trucks and shuttle buses with plug-in hybrid powertrain systems will be a key enabler in these micro-grid/V2G developments. Some of these have larger battery packs than do light-duty passenger PHEVs, and can thus play a significant role in a V2G micro-grid system on a military base. One concern is that only one diesel PHEV bus and one EV truck are listed so far on the GSA Schedule, and greater plug-in vehicle availability will be required to support these initiatives.

8.1 Availability of Commercial Hybrid-Electric Trucks and Buses for Non-tactical Applications

A variety of MD and HD hybrid trucks and buses has now joined the array of light-duty passenger hybrid vehicles available for government fleet ordering through the GSA Schedule. Hybrid trucks by Freightliner, Kenworth, and Navistar are available in various body configurations including cab & chassis, dump, stake bed, refrigerated, tractor, and cargo vans. Hybrid buses by International and Thomas Built come in various school and work bus configurations with multiple length/seating options, as well as shuttle buses including some from smaller coachbuilders.

The table below summarizes the hybrid truck and bus models now listed in the GSA 2012 Model Year Alternative Fuel Vehicle (AFV) Guide. A complete inventory with GSA Standard Item Numbers is included in Appendix C.

Table 14: Hybrid Truck and Bus Models Listed in 2012 GSA AFV Guide

Manufacturer	Model(s)	Configurations
Freightliner	M2 106 Hybrid	4x2 Cab & Chassis, Class 6 – 8 4x2 Dump, Class 6 – 8 4x2 Stake - 16/22 ft, Class 6 – 8 4x2 Van - 18 ft, Class 6
Kenworth	T270 Hybrid	4x2 Cab & Chassis, Class 6 – 7 4x2 Dump, Class 6 – 7 4x2 Refrig. Van - 14/16 ft, Class 6 – 7 4x2 Stake Bed - 16 ft, Class 6 4x2 Van - 18/20 ft, Class 6 – 7
	T370 Hybrid	4x2 Cab & Chassis, Class 8 4x2 Dump, Class 8 4x2 Refrig. Van - 20 ft, Class 8 4x2 Stake Bed - 22 ft, Class 8 4x2 Tractor, Class 7 4x2 Van - 22 ft, Class 8
Navistar	4000 Hybrid	4x2 Cab & Chassis, Class 7 – 8 4x2 Dump, Class 7 – 8 4x2 Refrig. Van - 16/20 ft, Class 7 – 8 4x2 Stake Bed - 22 ft, Class 8 4x2 Van - 20/22 ft, Class 7 – 8
IC Bus	CE Hybrid	28 – 40 Adult work bus 42 – 66 Child school bus
	CE Plug-in Hybrid	28 – 40 Adult work bus 42 – 66 Child school bus
	HC Commercial Hybrid	28/32/36 Adult MD Shuttle Bus, 94-102" W
Thomas Built	221 TS	28 Adult work bus 42 Child school bus
	251 TS	54 Child school bus
	281 TS	36 Adult work bus
	311 TS	66 Child school bus
	340 TS	40 Adult work bus

Source: Automotive Insight, based on GSA 2012 Model Year Alternative Fuel Vehicle (AFV) Guide dated 10/12/2011. Retrieved from <http://www.gsa.gov/graphics/fas/2012afvs.pdf>.

While these vehicles are listed in the GSA AFV Guide, a note indicates that a vehicle's presence is not a guarantee of item availability, only a show of contract award. A review of the GSA AutoChoice vehicle ordering website showed one MD/HD hybrid vehicle presently available for order on the Vehicle Availability Listing, the New Flyer Model DE40FLR 40 ft, 39-passenger hybrid transit bus (interestingly not listed in the AFV Guide).¹⁵⁶ Individual agencies need to check with AutoChoice or the Automotive Program Office to confirm availability of the other hybrid vehicle models. Another observation from the GSA Guide is that the price for the HEV version of most trucks listed above is around **4 – 5 percent less** than that of the comparable CNG version.

8.2 Support of Military Micro-grid and V2G Initiatives

The Office of the Secretary of Defense (OSD) has sponsored a Department of Defense (DOD) Plug-in Electric Vehicle Project team to develop planning for electrification of the non-tactical fleet. This team proposes to demonstrate vehicle-to-grid (V2G) and grid-to-vehicle (G2V) bi-directional power flow systems for use in grid services and energy system management (battery charging) with plug-in electric and plug-in hybrid electric vehicles. This is in support of a larger DOD initiative to develop micro-grids for military bases that can be supplied by renewable energy sources and utilized to charge plug-in hybrid and electric vehicles that are capable of sending power back into the micro-grid as required.

The majority of hybrid trucks and buses on the road today are charge-sustaining hybrids that do not require the vehicle to be plugged in to recharge the batteries, however, plug-in hybrid systems for trucks and buses are now coming into the market. Utility trucks that require jobsite power to operate on-board equipment and provide exportable power are among the first PHEV truck applications. Some of these vehicles are being equipped with two battery packs to provide sufficient power to allow the truck to operate the on-board equipment through a typical work shift on battery power without having to run the engine. This battery sizing will make these vehicles attractive for use in bi-directional power flow situations, where they can send power back into the grid through the charging equipment, if required.

These plug-in hybrid vehicles could be an important enabler in micro-grid/V2G developments for military bases. As with light-duty PHEVs, however, manufacturers are not specifically designing the truck PHEV hybrid systems or charging equipment to allow bi-directional power flow. The economic case for enabling V2G capability in vehicles will

¹⁵⁶ GSA AutoChoice Vehicle Availability Listing. Retrieved Jan. 15, 2012 from <https://apps.fas.gsa.gov/vehicles/roads/autochoice/closeoutdate.cfm>

need to be made, along with sufficient incentive for fleet operators to demand this capability in their hybrid vehicles. As the number of PHEV trucks and buses put into service grows, these vehicles may become a potential element of V2G implementations.

As of this writing, none of these PHEV trucks are listed in the GSA AFV Schedule, so they may not yet be available to military installations for use in a V2G system. The only MD or HD diesel PHEV presently listed by GSA is the CE model passenger bus produced by IC Bus that comes in school or work bus configurations. It is available as either a charge-sustaining (HEV) or charge-depleting (PHEV) hybrid. There is just one EV MD/HD truck on the GSA Schedule as well, that being the Smith EV 20 ft van in four configurations.

If the DOD is to be successful with planned V2G initiatives and micro-grid deployments that require plug-in hybrids or EVs on the base, they will need to work with GSA to significantly increase the availability of plug-in MD and HD vehicles that are available to government fleets.

9.0 Summary and Conclusions

Utilizing hybrid powertrain technology in Medium-Duty (MD) and Heavy-Duty (HD) trucks and buses provides the potential for much greater annual fuel savings than for passenger hybrids due to the significantly higher baseline fuel consumption of these large vehicles. An MD hybrid truck can save nearly four times as much fuel per year as a passenger hybrid. Additional benefits of hybridization can include quieter operation, reduced maintenance, and improved performance. Despite these benefits, market introduction of hybrid commercial trucks lags behind that of passenger hybrid vehicles.

- Diesel-electric hybrid transit buses have been in the North American market for over a decade, similar to passenger hybrid vehicles, but the development and market acceptance of hybrid trucks lags behind. The first commercial diesel-electric hybrid truck was produced by Navistar in 2007.
- A variety of diesel-electric hybrid truck entries have entered this market in the last 2 – 4 years and most U.S. truck and bus manufacturers now produce one or more hybrid models. MD delivery vehicles are presently one of the largest markets for hybrid trucks, while other popular applications include utility boom trucks and beverage haulers.
- Key drivers encouraging the development of MD and HD diesel-electric hybrid truck and bus offerings include proposals to regulate the fuel consumption of MD and HD trucks for the first time, government fleet efficiency mandates and electrified vehicle requirements, increasing fuel prices, and increasing availability of hybrid-electric truck and bus offerings and supporting technologies with declining cost.
- TARDEC has also promoted the development of diesel-electric hybrid truck technology through its creation and championship of the Hybrid Truck Users Forum (HTUF). This led to early fleet trials of hybrid trucks.
- The relatively low volumes per vehicle for many trucks have discouraged the introduction of hybrid powertrain technology since investment paybacks can be difficult to achieve. Both State and Federal government incentives have helped to stimulate demand, but the overall business case remains difficult.
- Developing hybrid-electric powertrains that will meet the unique load-carrying and duty cycle demands of large trucks and buses has required larger electrification components and energy storage mechanisms with higher operating voltages than for passenger hybrids, plus ways to handle the electrical load of on-board equipment for many truck types.
- The battery pack for a series hybrid-electric transit bus can require 7 – 10 times the energy and peak power as that for a passenger car hybrid. The typical operating voltage for the transit bus system is 600 volts DC with 333 amp current

vs. around 300 volts DC with 110 amp current in the passenger hybrid. Due to the much higher number of start-stop cycles on the transit bus, the energy throughput per day can be 375 kWh vs. just 3 kWh for the passenger hybrid.

- Ultracapacitors are beginning to be applied to hybrid-electric energy storage systems in transit buses and commercial trucks, with ISE Corporation particularly active in developing new systems.
- Eaton Corp. manufactures a parallel hybrid-electric drivetrain that is used by many of the truck Original Equipment Manufacturers (OEMs). Most of the hybrid buses use series hybrid-electric drivetrains, and key manufacturers are BAE Systems, ISE Corporation, and Allison Transmission.
- Eaton and Daimler disclosed plans to offer significantly more powerful diesel-electric hybrid systems with larger battery packs over the next two years.
- Some trucks also have unique requirements for on-board or exportable power that can be addressed in the hybrid system, thus avoiding the need for a separate motor to drive hydraulic pumps or an auxiliary power unit. This has made plug-in hybrids particularly attractive for utility trucks with deployable booms or buckets. It is possible to size the battery pack(s) large enough to run the auxiliary equipment on these trucks for a full day without starting the engine, and then recharge the battery pack from an off-board power source at night.
- Fleet managers for commercial vehicle fleets operating diesel hybrid trucks and buses were interviewed for this study in order to gain first-hand knowledge of their experiences. Key findings include:
 - Actual fuel savings have met expectations in some urban bus and delivery vehicle applications, but have fallen short in others. Route selection for hybrid delivery vehicles plays a big role in fuel savings realized, as does driver behavior.
 - Maintenance savings have been significant, and hybrid propulsion battery durability has been better than expected across most applications.
 - Drivers generally like the hybrids, finding that they are easy to drive, offer equivalent or better performance, and may be less fatiguing.
- There are now some hybrid trucks and buses available on the 2012 General Services Administration (GSA) Vehicle Schedule. This will help non-tactical fleets on U.S. bases meet goals for efficiency improvement and partial electrification. Tactical vehicles should benefit as well through technology transfer.
- Some MD and HD trucks and shuttle buses are now offering plug-in hybrid (PHEV) powertrain systems that have larger battery packs than do passenger PHEVs, and thus have the potential to play a role in a V2G energy storage and transfer system on a military base.

Appendix A: Heavy Hybrid Vehicles Qualifying for the Pre-2010 IRS Credit

The Alternative Motor Vehicle Credit, enacted by the Energy Policy Act of 2005, provided for four separate credits for different types of energy efficient vehicles. The amount of the potential credit varies by type of vehicle and which of the four credits applies. The vehicles listed below qualify as Qualified Heavy Hybrid Vehicles.

Qualifying Heavy Hybrid vehicles are new vehicles with a gross vehicle weight in excess of 8500 pounds that meet the definition of a qualifying hybrid vehicle. A qualifying hybrid vehicle means a motor vehicle which draws propulsion energy from onboard sources of stored energy which are either an internal combustion or heat engine using consumable fuel, and a rechargeable energy storage system. This section will **not** apply to vehicles purchased after 12-31-2009.

Manufactures of the vehicles listed below have provided appropriate information and have received from the Internal Revenue Service acknowledgement of the vehicles eligibility for the credit and the amount of the qualifying credit.¹⁵⁷

Qualified Heavy Hybrid Vehicles

(Applies only to vehicles acquired before 1-1-2010)

Azure Dynamics (AZD)

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2008	Ford E-450 Stripped or Cutaway Chassis Equipped with an Azure Dynamics Parallel Hybrid Electric System	14,050 lbs	\$3,000
2009	Ford E-450 Stripped or Cutaway Chassis equipped with an Azure Dynamics Parallel Hybrid Electric System	14,050 lbs	\$3,000
2010	Ford E-450 Stripped or Cutaway Chassis equipped with an Azure Dynamics Parallel Hybrid Electric System	14,050 lbs	\$3,000

¹⁵⁷ Source: IRS Website, Qualified Alternative Fuel Motor Vehicles (QAFMV) and Heavy Hybrid Vehicles, Updated 1-10-11. Retrieved Jan. 18, 2012 from <http://www.irs.gov/businesses/article/0,,id=175456,00.html>

Daimler Trucks North America-Freightliner/Eaton Corp.

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2008/2009/2010	Freightliner M2 Hybrid Delivery Vehicle with GVW of 19,501- 26,000lbs equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2008/2009/2010	Freightliner M2 Hybrid Delivery Vehicle with GVW of 26,001-33,000 lbs equipped with Eaton Hybrid System	26,001-33,000 lbs	\$12,000
2008/2009/2010	Freightliner M2 Hybrid Utility Vehicle with GVW of 19,501- 26,000 lbs equipped with Eaton Hybrid System including ePTO	19,501-26,000 lbs	\$6,000
2008/2009/2010	Freightliner M2 Hybrid Utility Vehicle GVW of 26,001 lbs and over equipped with Eaton Hybrid System including ePTO	26,000 lbs and over	\$12,000
2009/2010	Freightliner M2 Tractor equipped with Eaton Hybrid System	26,000 lbs and over	\$6,000

Freightliner Custom Chassis Corporation/Eaton Corporation

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2006	Freightliner MT45 Walk-In Truck with Utilimaster Body Equipped with Mercedes Benz OM904LA Engine and Eaton 44KW Hybrid Electric System	14,001lbs- 26,000lbs	\$4,500
2007	Freightliner MT45 Walk-In Truck with Utilimaster Body Equipped with Mercedes Benz OM904LA Engine and Eaton 44KW Hybrid Electric System	14,001lbs- 26,000lbs	\$4,500

International Truck and Engine Corporation/Eaton Corporation

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2006	International Utility Boom Vehicle; Model 4300SBA 4X2 w/ DT466 Engine and Eaton 44kW Hybrid Electric System	14,001 lbs- 26,000 lbs	\$6,000
2006	International Utility Boom Vehicle; Model 4300SBA 4X2 w/ DT466 Engine and Eaton 44kW Hybrid Electric System	26,000 lbs and over	\$12,000
2007	International Utility Boom Vehicle; Model 4300SBA 4X2 w/ DT466 Engine and Eaton 44kW Hybrid Electric System	14,001 lbs- 26,000 lbs	\$6,000
2007	International Utility Boom Vehicle; Model 4300SBA 4X2 w/ DT466 Engine and Eaton 44kW Hybrid Electric System	26,000 lbs and over	\$12,000

Kenworth Truck Company/Eaton Corporation

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2008	Kenworth Model T270 Utility Boom Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2008	Kenworth Model T370 Utility Boom Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2008	Kenworth Model T270 Package Delivery Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2008	Kenworth Model T370 Package Delivery Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2009	Kenworth Model T270 Utility Boom Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2009	Kenworth Model T270 Utility Boom Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2009	Kenworth Model T370 Utility Boom Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2009	Kenworth Model T370 Utility Boom Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2009	Kenworth Model T270 Package Delivery Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2009	Kenworth Model T270 Package Delivery Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2009	Kenworth Model T370 Package Delivery Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2009	Kenworth Model T370 Package Delivery Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2010	Kenworth Model T270 Package Delivery Vehicle Application GVW 19,501-26,000 lbs; Equipped w/ Eaton Hybrid Electric System	19,501-26,000 lbs	\$6,000
2010	Kenworth Model T370 Package Delivery Vehicle Application GVW 26,001-33,000 lbs; Equipped w/ Eaton Hybrid Electric System	26,001-33,000 lbs	\$12,000
2010	Kenworth Model T270 Utility Boom Vehicle Application GVW 19,501-26,000 lbs; Equipped w/ Eaton Hybrid Electric System	19,501-26,000 lbs	\$6,000
2010	Kenworth Model T370 Utility Boom Vehicle Application GVW 26,001-33,000 lbs; Equipped w/ Eaton Hybrid Electric System	26,001-33,000 lbs	\$12,000
2010	Kenworth T370 equipped with an Eaton Hybrid System		\$9,000

Navistar, Inc./Eaton Corporation

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2008	Navistar International DuraStar Hybrid Truck Model MA 02500 Equipped with an Eaton 10 HEV Hybrid System 13 GSC w/GVW 14,001-26,000	14,001-26,000 lbs	\$6,000
2009	Navistar International DuraStar Hybrid Truck Model MA 02500 Equipped with an Eaton 10 HEV Hybrid System 13 GSC w/GVW 14,001-26,000	14,001-26,000 lbs	\$6,000
2008	Navistar International DuraStar Hybrid Truck Model MA 02500 Equipped with an Eaton 10 HEV Hybrid System 13 GSC w/GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$12,000
2009	Navistar International DuraStar Hybrid Truck Model MA 02500 Equipped with an Eaton 10 HEV Hybrid System 13 GSC w/GVW 26,000-33,000 lbs	26,001-33,000 lbs	\$12,000
2008	Navistar International DuraStar Hybrid Truck Model MA 02500 Equipped with an Eaton 10 HEV Hybrid System 13GSB 14,000-26,000	14,001-26,000 lbs	\$3,000
2009	Navistar International DuraStar Hybrid Truck Model MA 02500 Equipped with an Eaton 10 HEV Hybrid System 13GSB 14,000-26,000	14,001-26,000 lbs	\$3,000
2008	Navistar International DuraStar Hybrid Truck Model MA 02500 Equipped with an Eaton 10 HEV Hybrid System 13GSB 6,000-33,000 lbs	26,001-33,000 lbs	\$6,000
2009	Navistar International DuraStar Hybrid Truck Model MA 02500 Equipped with an Eaton 10 HEV Hybrid System 13GSB 6,000-33,000 lbs	26,001-33,000 lbs	\$6,000
2008	Navistar International 3200 Bus Model PC 01500 Equipped with an Eaton 10HEV Hybrid System 13GSB 14,000-26,000 lbs GVW	14,001-26,000 lbs	\$3,000
2009	Navistar International 3200 Bus Model PC 01500 Equipped with an Eaton 10HEV Hybrid System 13GSB 14,000-26,000 lbs GVW	14,001-26,000 lbs	\$3,000
2008	Navistar International 3200 bus Model PC 01500 Equipped with an Eaton 10HEV Hybrid System 13GSB 26,001-33,000 GVW	26,001-33,000 lbs	\$6,000
2009	Navistar International 3200 bus Model PC 01500 Equipped with an Eaton 10HEV Hybrid System 13GSB 26,001-33,000 GVW	26,001-33,000 lbs	\$6,000
2009	Navistar IC Bus HC Series Commercial transit Bus Equipped with an Eaton 10HEV Hybrid System 13GSB GVW 14,001-26,000 lbs	14,001-26,000 lbs	\$3,000
2009	Navistar IC Bus HC Series Commercial transit Bus Equipped with an Eaton 10HEV Hybrid System 13GSB GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$6,000

Navistar/IC Bus LLC

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2008	Navistar IC Bus Model PB10500 CE Series Hybrid School Bus Equipped with the Enova Charge Depleting Hybrid Drive System GVW 14,001-26,000 lbs	14,001-26,000 lbs	\$6,000
2008	Navistar IC Bus Model PB10500 CE Series Hybrid School Bus Equipped with the Enova Charge Depleting Hybrid Drive System GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$12,000
2009	Navistar IC Bus Model PB10500 CE Series Hybrid School Bus Equipped with the Enova Charge Depleting Hybrid Drive System GVW 14,001-26,000 lbs	14,001-26,000 lbs	\$6,000
2009	Navistar IC Bus Model PB10500 CE Series Hybrid School Bus Equipped with the Enova Charge Depleting Hybrid Drive System GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$12,000
2008	Navistar IC Bus Model PC10500 CE Series Commercial Bus Equipped with the Enova Charge Depleting Hybrid Drive System GVW 14,001-26,000 lbs	14,001-26,000 lbs	\$6,000
2008	Navistar IC Bus Model PC10500 CE Series Commercial Bus Equipped with the Enova Charge Depleting Hybrid Drive System GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$12,000
2009	Navistar IC Bus Model PC10500 CE Series Commercial Bus Equipped with the Enova Charge Depleting Hybrid Drive System GVW 14,001-26,000 lbs	14,001-26,000 lbs	\$6,000
2009	Navistar IC Bus Model PC10500 CE Series Commercial Bus Equipped with the Enova Charge Depleting Hybrid Drive System GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$12,000

Navistar 2010 IC Buses

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2010	IC Bus Model PB 10500 CE Series Hybrid School Bus Powered by MaxxForce 7 Diesel Engine GVW 14,001-26,000 lbs	14,001-26,000 lbs	\$6,000
2010	IC Bus Model PB 10500 CE Series Hybrid School Bus Powered by MaxxForce 7 Diesel Engine GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$12,000
2010	IC Bus Model PC 10500 CE Series Hybrid Commercial Bus Powered by MaxxForce 7 Diesel Engine GVW 14,001-26,000 lbs	14,001-26,000 lbs	\$6,000
2010	IC Bus Model PB 10500 CE Series Hybrid Commercial Bus Powered by MaxxForce 7 Diesel Engine GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$12,000
2010	IC Bus Model PC50500 HC Series Hybrid Commercial Transit Bus Powered by MaxxForce DT Engine; GVW 14,001-26,000 lbs	14,001-26,000 lbs	\$3,000
2010	IC Bus Model PC50500 HC Series Hybrid Commercial Transit Bus Powered by MaxxForce DT Engine; GVW 26,001-33,000 lbs	26,001-33,000 lbs	\$6,000

Odyne/Navistar Qualified Vehicle – Heavy Hybrid

Model Year	Vehicle Description	Credit Amount
2009	Navistar International DuraStar 4x2 Utility Truck Equipped with the Odyne Hybrid Electric System	\$12,000

Peterbilt Motors Co./Eaton Corporation

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2008	Peterbilt Model 330 Utility Boom Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2008	Peterbilt Model 335 Utility Boom Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2008	Peterbilt Model 330 Package Delivery Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2008	Peterbilt Model 335 Package Delivery Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2009	Peterbilt Model 330 Utility Boom Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2009	Peterbilt Model 330 Utility Boom Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2009	Peterbilt Model 335 Utility Boom Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2009	Peterbilt Model 335 Utility Boom Vehicle with GVW > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2009	Peterbilt Model 330 Package Delivery Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2009	Peterbilt Model 330 Package Delivery Vehicle with GVW of > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2009	Peterbilt Model 335 Package Delivery Vehicle with GVW of 19,501-26,000 lbs and Equipped with Eaton Hybrid System	19,501-26,000 lbs	\$6,000
2009	Peterbilt Model 335 Package Delivery Vehicle with GVW > 26,000 lbs and Equipped with Eaton Hybrid System	>26,000 lbs	\$12,000
2010	Peterbilt Model 330 Package Delivery Vehicle Application GVW 19,501-26,000 lbs; Equipped w/ Eaton Hybrid Electric System	19,501-26,000 lbs	\$6,000
2010	Peterbilt Model 335 Package Delivery Vehicle Application	26,001-	\$12,000

	GVW 26,001-33,000 lbs; Equipped w/ Eaton Hybrid Electric System	33,000 lbs	
2010	Peterbilt Model 330 Utility Boom Vehicle Application GVW 19,501-26,000 lbs; Equipped w/ Eaton Hybrid Electric System	19,501-26,000 lbs	\$6,000
2010	Peterbilt Model 335 Utility Boom Vehicle Application GVW 26,001-33,000 lbs; Equipped w/ Eaton Hybrid Electric System	26,001-33,000 lbs	\$12,000
2010	Peterbilt Model 335 equipped with an Eaton Hybrid System		\$9,000

Peterbilt Motors – 2010 Vehicles

Model Yr Effective 10-31-09	Vehicle Description	Gross Vehicle Weight	Credit Amount
2010	Peterbilt Model 330 Package Delivery Vehicle Application GVW 19,501-26,000 lbs; Equipped w/ Eaton Hybrid Electric System	19,501-26,000 lbs	\$6,000
2010	Peterbilt Model 337 Package Delivery Vehicle Application GVW > 26,000 lbs; Equipped w/ Eaton Hybrid Electric System	> 26,000 lbs	\$12,000
2010	Peterbilt Model 330 Utility Boom Vehicle Application GVW 19,501-26,000 lbs; Equipped w/ Eaton Hybrid Electric System	19,501-26,000 lbs	\$6,000
2010	Peterbilt Model 337 Utility Boom Vehicle Application GVW > 26,000 lbs; Equipped w/ Eaton Hybrid Electric System	> 26,000 lbs	\$12,000
2010	Peterbilt Model 348 Utility Boom Vehicle Application GVW > 26,000 lbs; Equipped w/ Eaton Hybrid Electric System	> 26,000 lbs	\$12,000
2010	Peterbilt Model 337 Tractor GCVW 26,000-55,000 lbs; Equipped w/Eaton hybrid Electric System	26,000-55,000 lbs GCVW	\$9,000
2010	Peterbilt Model 348 Tractor GCVW 26,000-55,000 lbs; Equipped w/Eaton hybrid Electric System	26,000-55,000 lbs GCVW	\$9,000

2007 Workhorse Custom Chassis/Eaton Corporation

Model Year	Vehicle Description	Gross Vehicle Weight	Credit Amount
2007	Workhorse Model W62 Walk In Truck Equipped with a Morgan-Olson Body, Model Year 2006 International VT275 Engine and a 2007 Model Year Eaton Hybrid Electric System	19,500-26,000 lbs	\$3,000

Appendix B: Lithium Battery Technology Trends and Supply Considerations

Lithium-ion Battery Technology

Lithium-ion (Li-ion) batteries are attractive for electrified vehicle applications because of their relatively high energy densities per unit mass, volume, and cost. Lithium based chemistries have three times the energy density of other systems like nickel metal-hydride (Ni-MH) and nickel-cadmium (Ni-Cd). Unlike Ni-Mh, where there is only one set of components and chemical reactions, many different materials are used in Li-ion batteries.

A battery is rated in terms of its energy, which is the voltage times the capacity. Thus, higher voltage and higher capacity materials will contain more energy. Energy may be measured in terms of weight or volume; these metrics are called specific energy and energy density, respectively. The energy density and specific energy represent the maximum energy that may be obtained from a material. The specific energy in Watt-hours per kilogram (Wh/kg) versus the energy density in watt-hours per liter (Wh/L) of different battery types is illustrated in the figure below.

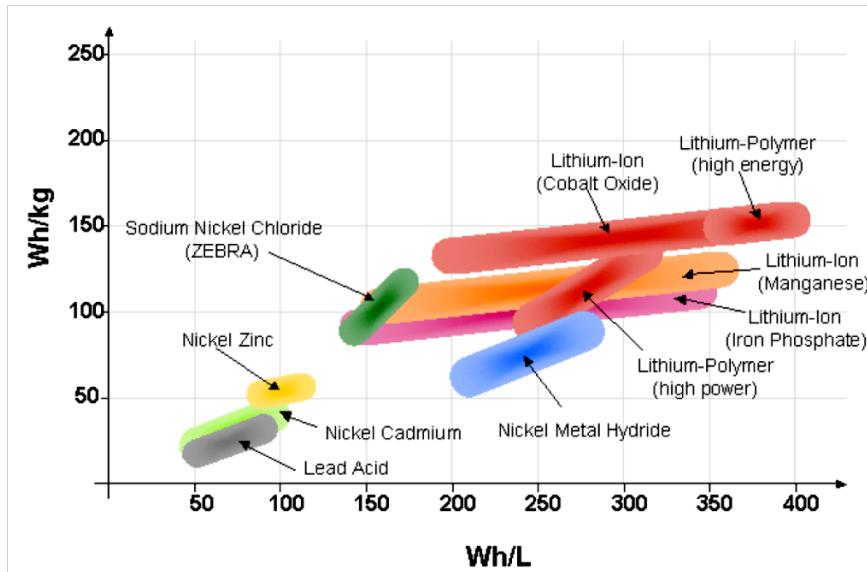


Figure 77: Specific Energy and Energy Density of Various Battery Types

Source: Center for Entrepreneurship & Technology (CET), U-Cal Berkley. (December 21, 2009). The Electric Vehicle Battery Landscape: Opportunities and Challenges.

It can be seen that lithium ion battery systems contain more energy than nickel metal hydride, nickel cadmium, or lead acid batteries. There are many different materials that may be used for lithium ion batteries. For example, the red line in the chart represents the energy available when lithium cobalt oxide is used, while the pink line shows the energy available when the battery is made of lithium iron phosphate. This variation allows manufacturers to tailor their products to a specific application and provides a basis for competitive advantage for battery producers.¹⁵⁸

One of the key factors determining the energy contained in a battery is the choice of materials for the anode and cathode. The vast majority of batteries currently commercialized use graphitic carbon anodes. Significantly more variety exists in the choice of cathode materials. The figure below shows the potential of several cathode materials versus capacity, which represents the amount of charge contained in the material. Higher capacity and higher voltage can both yield more energy. The cathode materials pictured are lithium cobalt oxide (LiCoO_2 or LCO), lithium manganese oxide (LiMn_2O_4 or LMO), lithium iron phosphate (LiFePO_4 or LFP), and lithium nickel manganese cobalt oxide ($\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$).

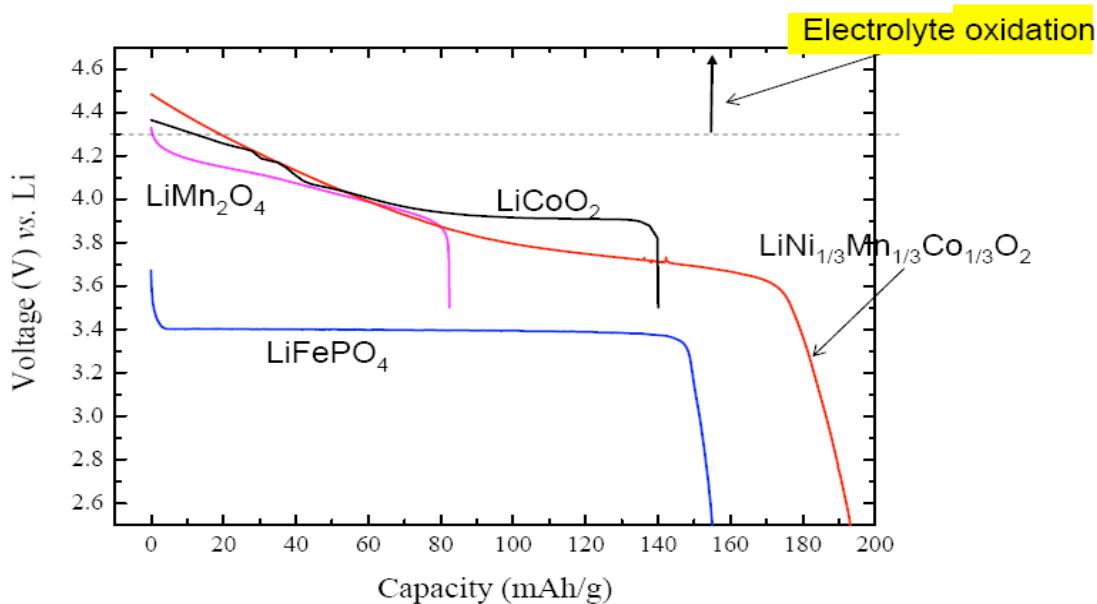


Figure 78: Energy Potential of Li-ion Battery Cathode Materials

Source: Center for Entrepreneurship & Technology (CET), U-Cal Berkley. The Electric Vehicle Battery Landscape: Opportunities and Challenges.

¹⁵⁸ Center for Entrepreneurship & Technology (CET), U-Cal Berkley. (December 21, 2009). The Electric Vehicle Battery Landscape: Opportunities and Challenges.

LCO has historically been the leading lithium-ion battery technology and has the highest energy density of the currently commercialized materials. LCO, made by companies like Panasonic, is used in laptops and other portable electronics, as well as the Tesla Roadster. LMO is also a well-studied material that is currently used in batteries produced by companies including LG Chem and Automotive Energy Supply Corp. (AESC). The energy density and operating voltage are lower than that of LCO. LFP is a lower-voltage, lower energy material with the advantage that it is environmentally benign and less expensive. LFP batteries are produced by A123 Systems.¹⁵⁹

Some product specifications for batteries using these cathode materials are shown in the table below.

Table 15: Key Battery Specifications for Selected Chemistries

Manufacturer	A123	CPI (LG)	Panasonic
Chemistry	Lithium iron phosphate	Lithium manganese oxide spinel	Lithium cobalt oxide
Specific Power (W/kg)	3000	2000	1200
Specific Energy (Wh/kg)	108	80	175
Power Density (W/L)	5800	N/A	N/A
Energy Density (Wh/L)	145	N/A	N/A
Cycle Life (10C, 100% DOD)	>1000 cycles	1000 cycles	>200 cycles
Operating Temperature	-30 to 60 °C	-30 to 60 °C	-30 to 60 °C
Calendar Life	10 yrs	N/A	15 yrs

(N/A indicates that information for this company was not available.)

Source: Ohzuku, T., Brodd, R.J. Journal of Power Sources 174. 449–456. (2007)

Lithium Battery Innovation Leaders

The widespread usage of Li-ion batteries for present HEV, PHEV and EV vehicles has attracted an increasing number of battery manufacturers to an already crowded market. A 2011 report by Lux Research questions whether all of these companies can survive without forging new partnerships. Lux has compared the Business Execution and Technical Value of the various Li-ion battery developers on what it calls the Lux

¹⁵⁹ Center for Entrepreneurship & Technology (CET), U-Cal Berkley. (December 21, 2009). The Electric Vehicle Battery Landscape: Opportunities and Challenges.

Innovation Grid, helping to identify which will make the strongest potential partners as the electric vehicle market matures. This Grid is shown in the figure below.¹⁶⁰

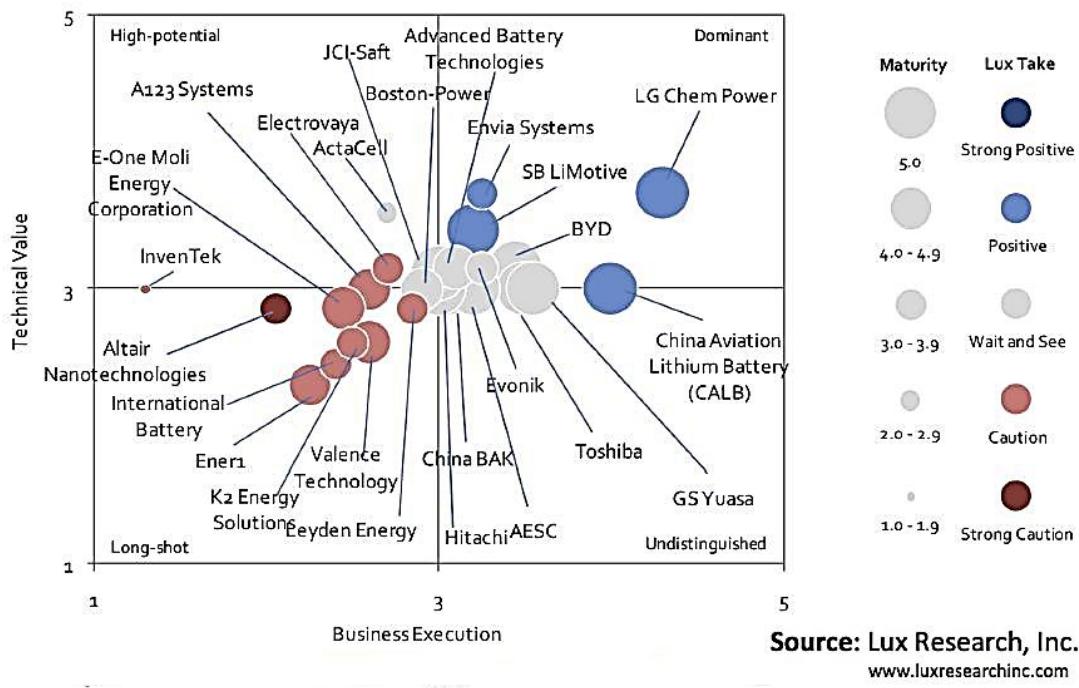


Figure 79: Lux Research Li-ion Battery Innovation Grid

Source: Lux Research. Using Partnerships to Stay Afloat in the Electric Vehicle Storm.

Lux indicates that LG Chem Power stands out versus its competition in the graphic's Dominant Quadrant. LG Chem owes its strong technical value to its high-energy lithium-manganese-spinel-based cells and strong cycle life, both of which come at costs that are among the most competitive in the market. Its multitude of supply partnerships with the likes of GM, Eaton, and Ford, however, justify the company's strong Business Execution score.

Significant enhancements in specific energy and a commensurate reduction in cell cost has garnered Envia Systems the attention of major investors including GM, Asahi Glass, and Asahi Kasei. Yet serious competition remains for Envia in cathode materials, including two major corporations in BASF and Toda Kogyo licensing the same Argonne National Laboratory technology that Envia's materials are based on.

¹⁶⁰ See, Kevin. (September 30, 2011). Ranking Li-ion battery developers on the Lux Innovation Grid. Retrieved from <http://www.luxresearchinc.com/blog/tag/lg-chem/>

China is home to a number of top contenders, thanks to the Chinese government's desire to keep the electric vehicle value chain inside China's borders. But batteries from China BAK, BYD, and China Aviation Lithium Battery (CALB) are undifferentiated technologically, and may not share the quality of cells manufactured outside of China.

Battery Supply Implications

A key issue that may impact battery manufacturing and prices going forward is the projected excess capacity now developing in the industry. According to a 2011 report by Lux Research, the supply of batteries for electric vehicles could far surpass the demand for electric vehicles over the next few years. Lux calls it a "severe mismatch," and one that will cause consolidation, the need for increased partnerships between battery makers and auto manufacturers, and the need for new markets for battery makers to sell into.

Battery makers have been expanding EV/HEV battery capacity substantially, and new battery makers are also moving into this market. However, the market for electrified vehicles is shaping up to be much smaller than some have predicted, at least in the short term. As a result, Lux says that even if oil prices jump to \$200 per barrel, which could cause the EV market to grow substantially by 2020, five of the leading battery makers — LG Chem, GS Yuasa, SB LiMotive, AESC, and Sanyo — would have enough capacity to manufacture far more batteries than needed to cover that market. That means there will be dozens of battery makers with way too much supply, particularly if gas prices remain low.

This will likely drive consolidation and new partnerships in the electrified vehicle battery industry. Small, innovative technology developers will be able to do licensing deals and be acquired, says Lux. Other companies may choose to find battery markets outside of pure EVs, like hybrid vehicles, e-bikes, and the power grid.

Appendix C: MD and HD Hybrid Vehicles Listed in 2012 GSA AFV Schedule

Vehicle Configuration	GSA Std. Item No.	Fuel Type	Manufacturer	Model	Selling Price (\$)
<u>TRUCKS</u>					
4X2 CAB AND CHASSIS, MIN. 21,000 LBS GVWR	414	DIESEL HEV	FREIGHTLINER/DAIMLER	M2 106	88,536.60
	414	DIESEL HEV	KENWORTH	T270	105,234.93
4X2 CAB AND CHASSIS, MIN. 25,500 LBS GVWR	511	DIESEL HEV	FREIGHTLINER/DAIMLER	M2 106	89,460.75
	511	DIESEL HEV	NAVISTAR	4000	93,268.45
	511	DIESEL HEV	KENWORTH	T270	106,570.15
4X2 CAB AND CHASSIS, MIN. 33,000 LBS GVWR	513	DIESEL HEV	FREIGHTLINER/DAIMLER	M2 106	93,723.96
	513	DIESEL HEV	NAVISTAR	4000	98,326.53
	513	DIESEL HEV	KENWORTH	T370	105,784.37
4X2 CAB AND CHASSIS, MIN. 35,000 LBS GVWR	514	DIESEL HEV	NAVISTAR	4000	110,122.32
4X2 DUMP, MIN. 21,000 LBS GVWR	444	DIESEL HEV	FREIGHTLINER/DAIMLER	M2 106	104,670.34
	444	DIESEL HEV	KENWORTH	T270	116,716.61
4X2 DUMP, MIN. 25,500 LBS GVWR	541	DIESEL HEV	FREIGHTLINER/DAIMLER	M2 106	105,284.42
	541	DIESEL HEV	NAVISTAR	4000	106,880.22
	541	DIESEL HEV	KENWORTH	T270	117,951.84
4X2 DUMP, MIN. 33,000 LBS GVWR	543	DIESEL HEV	FREIGHTLINER/DAIMLER	M2 106	109,068.89
	543	DIESEL HEV	NAVISTAR	4000	111,246.45
	543	DIESEL HEV	KENWORTH	T370	119,175.96
4X2 DUMP, MIN. 35,000 LBS GVWR	544	DIESEL HEV	NAVISTAR	4000	125,476.34
4X2 REFRIGERATOR VAN, 14 FT, MIN. 21,000 LBS GVWR	484	DIESEL HEV	KENWORTH	T270	136,549.98
4X2 REFRIGERATOR VAN, 16 FT, MIN. 25,500 LBS GVWR	581	DIESEL HEV	NAVISTAR	4000	133,062.45
	581	DIESEL HEV	KENWORTH	T270	144,661.29
4X2 REFRIGERATED VAN, 20 FT, MIN. 33,000 LBS. GVWR	583	DIESEL HEV	NAVISTAR	4000	136,528.77
	583	DIESEL HEV	KENWORTH	T370	142,836.22
4X2 STAKE, 16 FT, MIN. 21,000 LBS GVWR	434	DIESEL HEV	FREIGHTLINER/DAIMLER	M2 106	92,962.42
	434	DIESEL HEV	KENWORTH	T270	108,621.46

Vehicle Configuration	GSA Std. Item No.	Fuel Type	Manufacturer / Dealer	Model	Selling Price (\$)
4X2 STAKE, 22 FT, MIN. 33,000 LBS GVWR	533	DIESEL HEV	FREIGHTLINER/ DAIMLER	M2 106	97,139.78
	533	DIESEL HEV	NAVISTAR	4000	97,289.26
	533	DIESEL HEV	KENWORTH	T370	109,810.23
4X2 TRACTOR, MIN. 29,000 LBS GVWR	522	DIESEL HEV	KENWORTH	T370	116,681.26
4X2 VAN, 18 FT, MIN 21,000 LBS GVWR	474	DIESEL HEV	FREIGHTLINER/ DAIMLER	M2 106	97,318.55
	474	DIESEL HEV	KENWORTH	T270	114,759.23
4X2 VAN, 20 FT, MIN. 25,500 LBS GVWR	571	DIESEL HEV	NAVISTAR	4000	109,362.80
	571	DIESEL HEV	KENWORTH	T270	122,669.55
4X2 VAN, 22 FT, MIN. 33,000 LBS GVWR	573	DIESEL HEV	NAVISTAR	4000	111,711.05
	573	DIESEL HEV	KENWORTH	T370	119,585.01
<u>BUSES</u>					
28 ADULT, TYPE C, WORK BUS, BASIC	220A	DIESEL HEV	Thomas Built	221TS	119,189.09
	220A	DIESEL HEV	IC Bus	CE Hybrid	149,992.07
	220A	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	188,097.45
42 CHILDREN, TYPE C, SCHOOL BUS, BASIC	220C	DIESEL HEV	Thomas Built	221TS	117,801.35
	220C	DIESEL HEV	IC Bus	CE Hybrid	149,604.23
	220C	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	187,457.01
36 ADULT, TYPE C, WORK BUS, BASIC	221A	DIESEL HEV	Thomas Built	281TS	120,530.37
	221A	DIESEL HEV	IC Bus	CE Hybrid	156,762.10
	221A	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	194,867.48
54 CHILDREN, TYPE C, SCHOOL BUS, BASIC	221C	DIESEL HEV	Thomas Built	251TS	118,718.43
	221C	DIESEL HEV	IC Bus	CE Hybrid	153,343.25
	221C	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	191,511.15
40 ADULT, TYPE C, WORK BUS, BASIC	222A	DIESEL HEV	Thomas Built	340TS	121,242.42
	222A	DIESEL HEV	IC Bus	CE Hybrid	156,811.59
	222A	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	194,916.97
66 CHILDREN TYPE C, SCHOOL BUS, BASIC	222C	DIESEL HEV	Thomas Built	311TS	119,131.52
	222C	DIESEL HEV	IC Bus	CE Hybrid	153,901.78
	222C	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	192,069.68
28 ADULT, TYPE C, WORK BUS	320A	DIESEL HEV	Thomas Built	221TS	122,200.91

Vehicle Configuration	GSA Std. Item No.	Fuel Type	Manufacturer / Dealer	Model	Selling Price (\$)
42 CHILDREN, TYPE C, SCHOOL BUS	320C	DIESEL HEV	Thomas Built	221TS	121,055.57
	320C	DIESEL HEV	IC Bus	CE Hybrid	153,355.57
	320C	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	191,179.87
36 ADULT, TYPE C, WORK BUS	321A	DIESEL HEV	Thomas Built	281TS	129,845.60
	321A	DIESEL HEV	IC Bus	CE Hybrid	164,111.87
54 CHILDREN, TYPE C, SCHOOL BUS	321C	DIESEL HEV	Thomas Built	251TS	126,667.13
	321C	DIESEL HEV	IC Bus	CE Hybrid	161,409.11
	321C	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	195,118.87
40 ADULT, TYPE C, WORK BUS	322A	DIESEL HEV	Thomas Built	340TS	131,200.01
	322A	DIESEL HEV	IC Bus	CE Hybrid	164,822.91
	322A	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	202,928.29
66 CHILDREN, TYPE C, SCHOOL BUS	322C	DIESEL HEV	Thomas Built	311TS	127,145.87
	322C	DIESEL HEV	IC Bus	CE Hybrid	162,310.03
	322C	PLUG-IN HEV	IC Bus	CE Plug-in Hybrid	196,019.79
28 ADULT, 100-102 INCH WIDE, MEDIUM-DUTY SHUTTLE BUS, BASIC	259W	DIESEL HEV	IC Bus	HC Commercial Hybrid	156,985.91
	259W	DIESEL HEV	Capitol Coachworks	Turtle Top Odyssey XL	176,037.95
32 ADULT, 94-99 INCH WIDE, MEDIUM-DUTY SHUTTLE BUS, BASIC	260	DIESEL HEV	Masters Transportation	Goshen Coach Sentinel	145,458.18
	260	DIESEL HEV	IC Bus	HC Commercial Hybrid	152,459.71
32 ADULT, 100-102 INCH WIDE, MEDIUM-DUTY SHUTTLE BUS, BASIC	260W	DIESEL HEV	IC Bus	HC Commercial Hybrid	157,295.98
	260W	DIESEL HEV	Capitol Coachworks	Turtle Top Odyssey	178,068.05
36 ADULT, 94-99 INCH WIDE, MEDIUM-DUTY, SHUTTLE BUS, BASIC	263	DIESEL HEV	Masters Transportation	Goshen Coach Sentinel	153,047.32
	263	DIESEL HEV	IC Bus	HC Commercial Hybrid	163,600.81
36 ADULT, 100-102 INCH WIDE, MEDIUM-DUTY SHUTTLE BUS, BASIC	263W	DIESEL HEV	IC Bus	HC Commercial Hybrid	164,633.03
	263W	DIESEL HEV	Capitol Coachworks	Turtle Top Odyssey	183,869.49

Source: Automotive Insight, based on GSA 2012 Model Year Alternative Fuel Vehicle (AFV) Guide dated 10/12/2011. Retrieved from <http://www.gsa.gov/graphics/fas/2012afvs.pdf>.